Electron Bernstein Wave Studies on COMPASS-D and MAST

V. Shevchenko

EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxfordshire, OX14 3DB, UK

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Outline

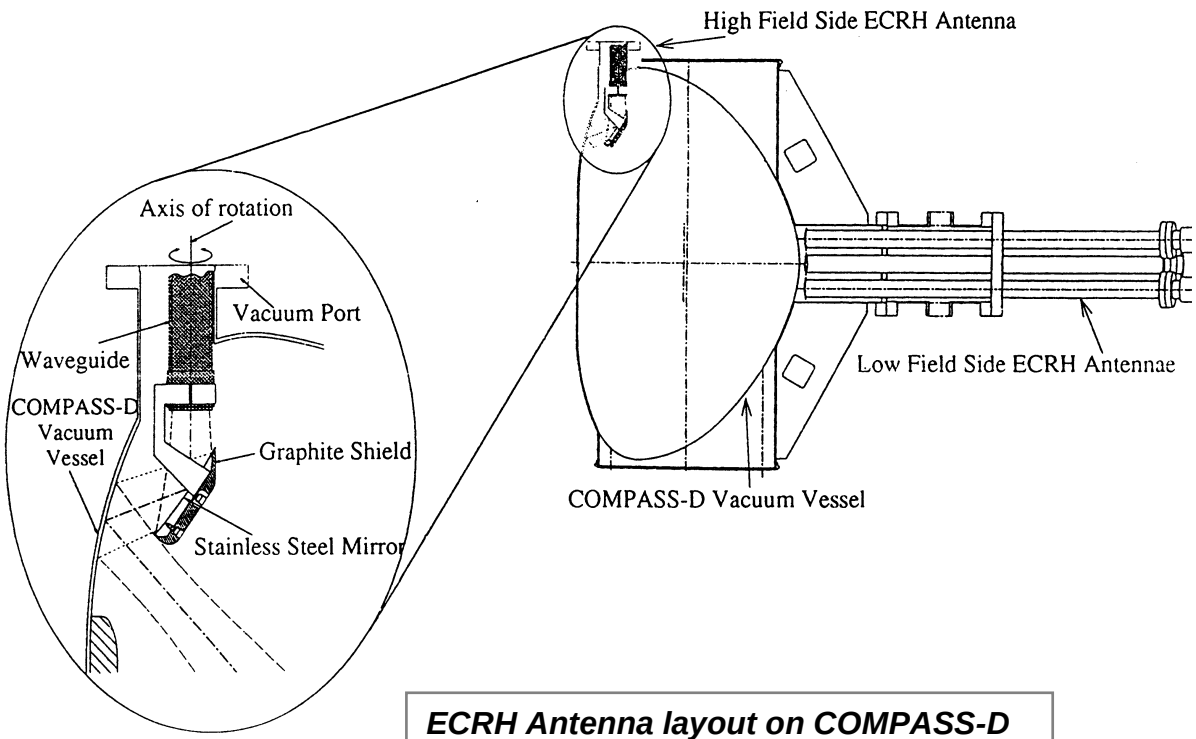
- Motivations
- EBW heating and current drive experiments on COMPASS-D
- EBW emission observations on MAST
- Preliminary results of ECRH breakdown and EBW heating experiments on MAST

Motivations

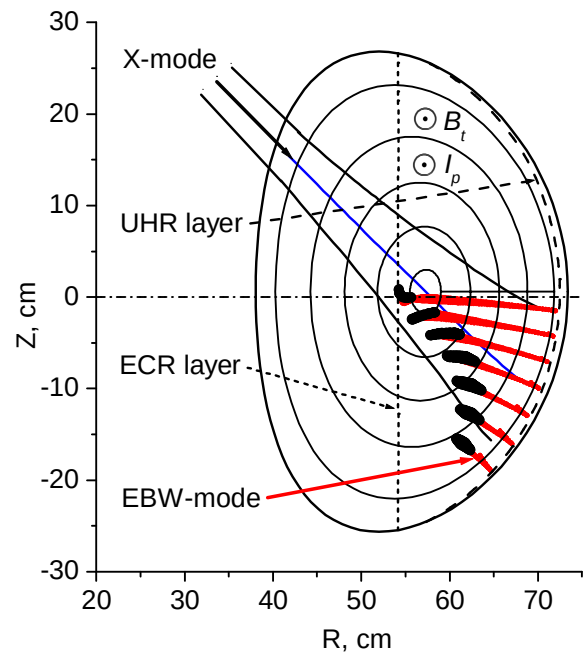
- Electron Bernstein waves (EBW) have potential for providing efficient heating and current drive in overdense plasmas ($\omega_{ce} < \omega_{pe}$):
  - **EBWs have no density limit (no high density cut-off)**
  - **EBWs experience strong damping on electrons near the Doppler-shifted electron cyclotron (EC) resonance and its harmonics**

- EBWs are predominantly electrostatic waves and do not exist in vacuum. They can be excited with e/m waves launched from vacuum:
  - **via X-B or O-X-B mode conversion mechanisms with ECRF power launch from the low field side ($\omega_{RF} > \omega_{ce}$) or**
  - **via direct coupling of the slow X-mode into EBW at the UHR with ECRF power launch from the high field side ($\omega_{RF} < \omega_{ce}$)**

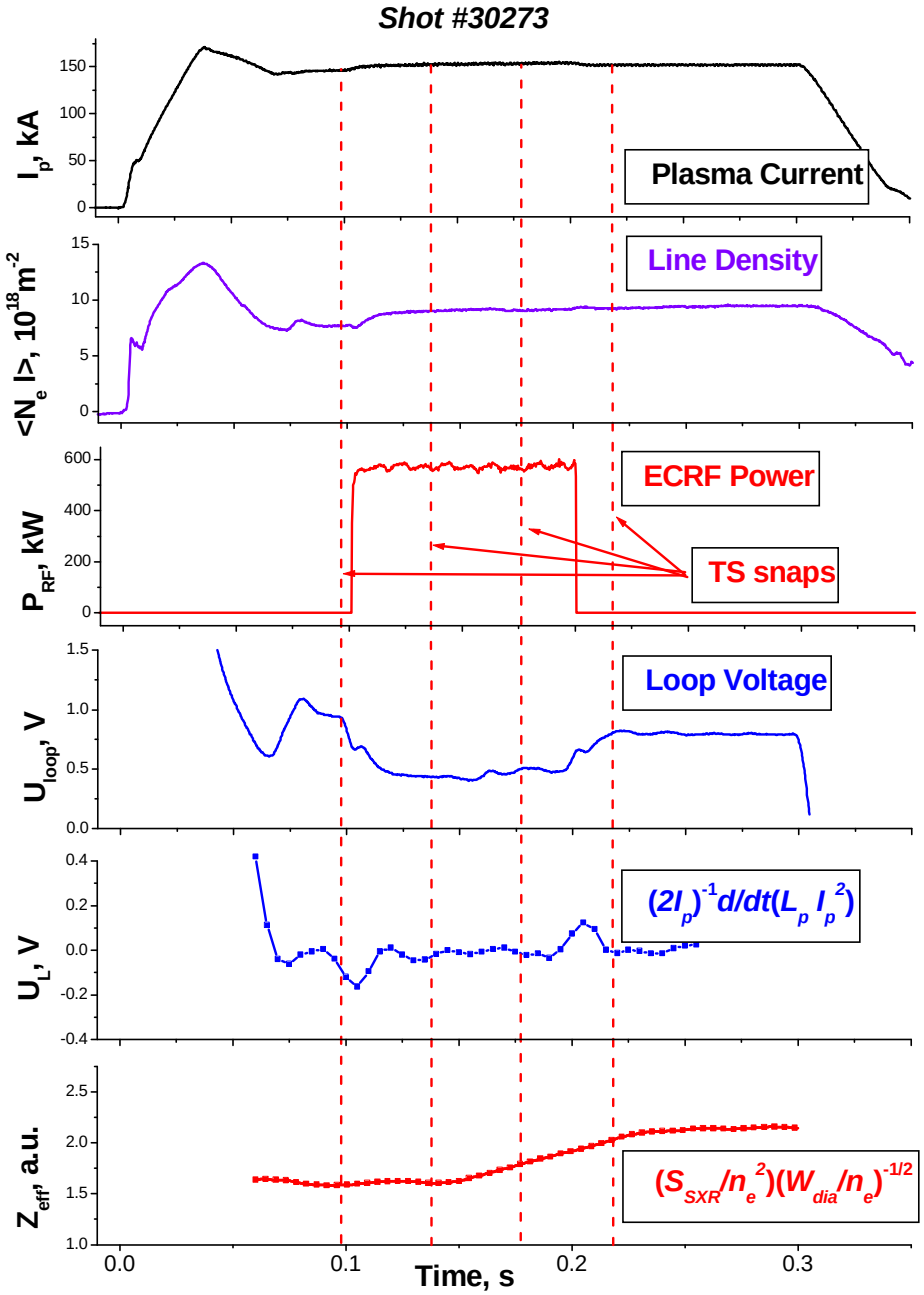
Experimental Layout



ECRH Antenna layout on COMPASS-D



The schematic of EBW heating and CD experiment on COMPASS-D



Experimental Set-up

A highly reproducible plasma has been chosen as a target

- Major radius R = 0.56 m
- Minor radius a = 0.2 m
- Elongation κ = 1.73
- Triangularity δ = 0.22
- Plasma current I_p = 150 kA
- Toroidal field B_o = 2.05 T

From shot to shot the toroidal launch angle was changed from -32.6° to +32.6° with a step of ~8°

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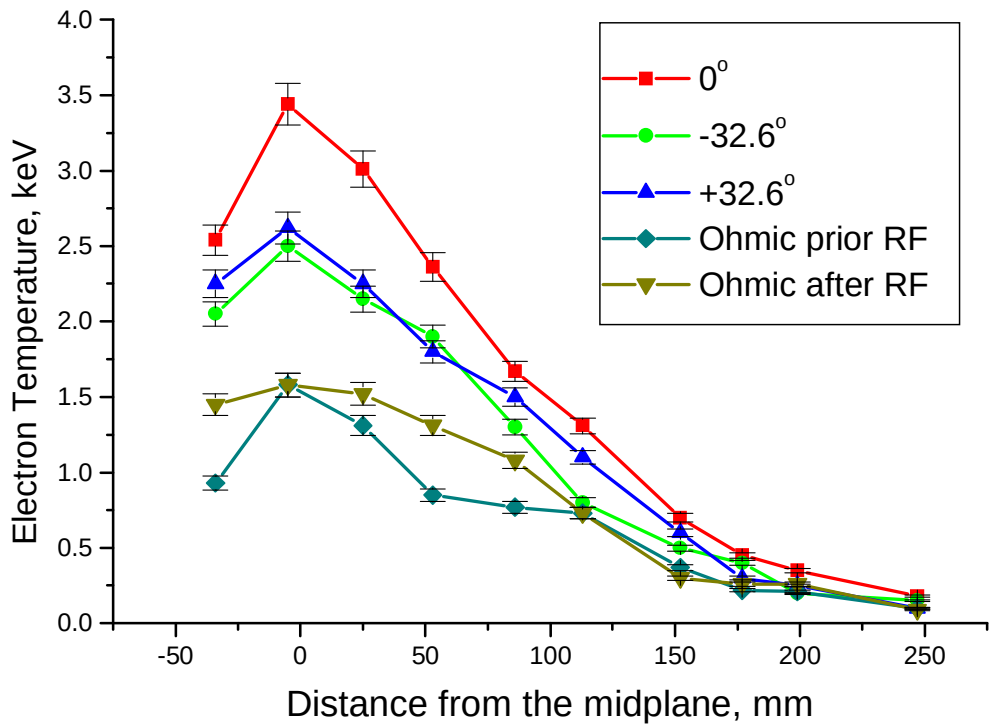
Experimental Results



TS electron temperature profiles measured at different launch angles during ECRH

- **Electron temperature during ECRH is higher for launch angles close to perpendicular to the magnetic field**
- **Electron temperature profile does not show any significant transformations, such as peaking or flattening, in a whole range of launch angles**

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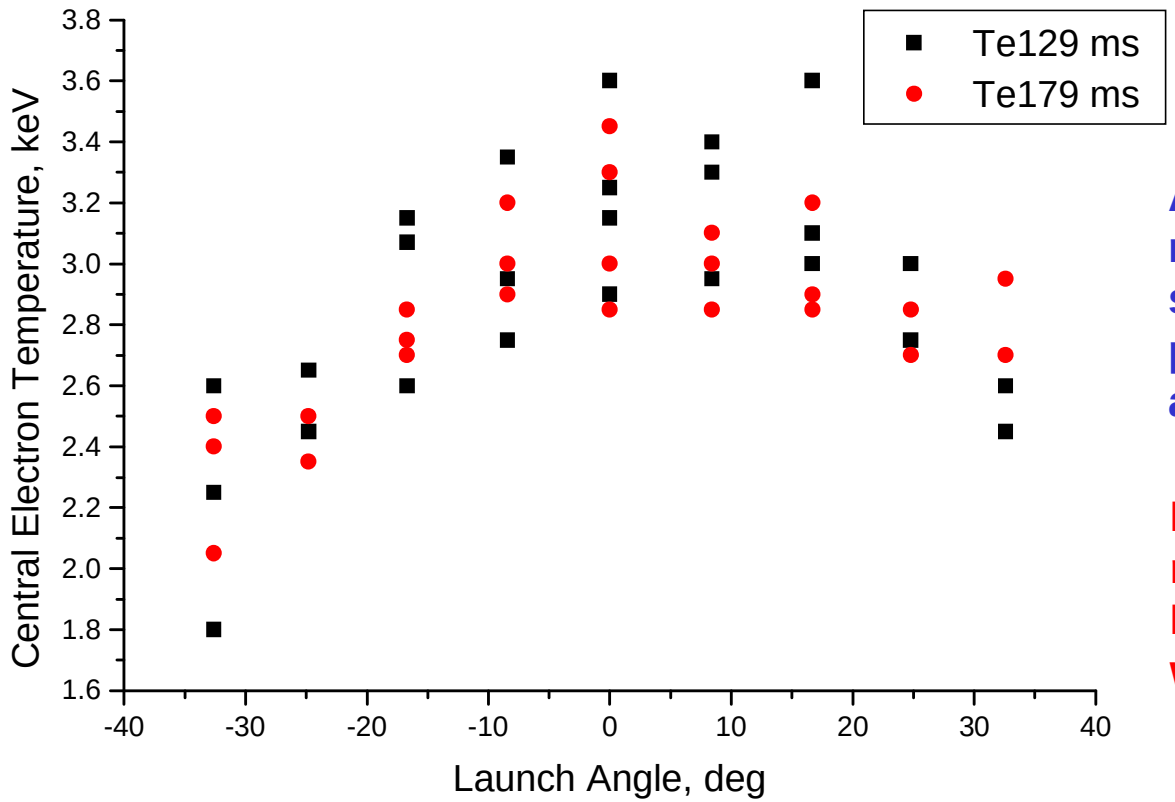
Heating Efficiency

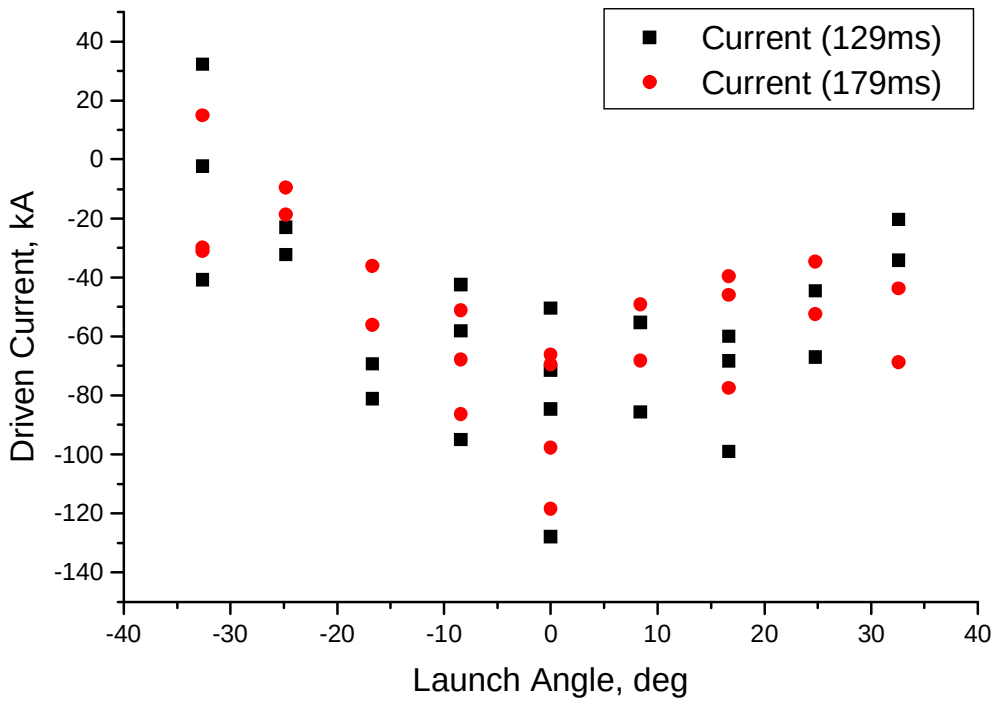


Central electron temperature during ECRH against toroidal launch angle counted from perpendicular to the magnetic field

At perpendicular launch X-mode absorption is small, so plasma heating is predominantly due to EBW absorption

ECRF plasma heating is much more effective via X-EBW mode excitation than with the use of pure X-mode

EBW Current Drive



Non-inductive current driven in the plasma estimated from experimental data

- **Assuming small changes in profile shapes, T_e, Z_{eff} and j_p, one can estimate the non-inductive current using simple relation**

$$I_{CD} = I_p - I_{BS}^{ECRH} - (I_p - I_{BS}^{OH}) \frac{V_{loop}^{ECRH}}{V_{loop}^{OH}} \left(\frac{T_e^{ECRH}}{T_e^{OH}} \right)^{\frac{3}{2}}$$

- **Bootstrap current varies from 15 to 21 kA over the range of launch angles**

Electron temperature rise and loop voltage decrease are consistent with a non-inductive current of ~100 kA driven in the counter direction

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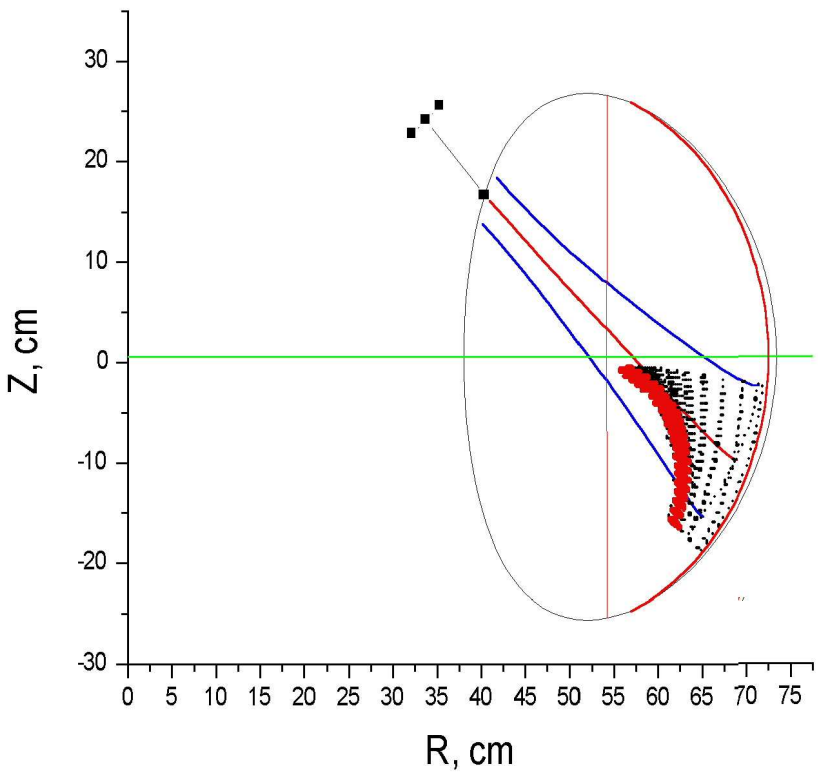
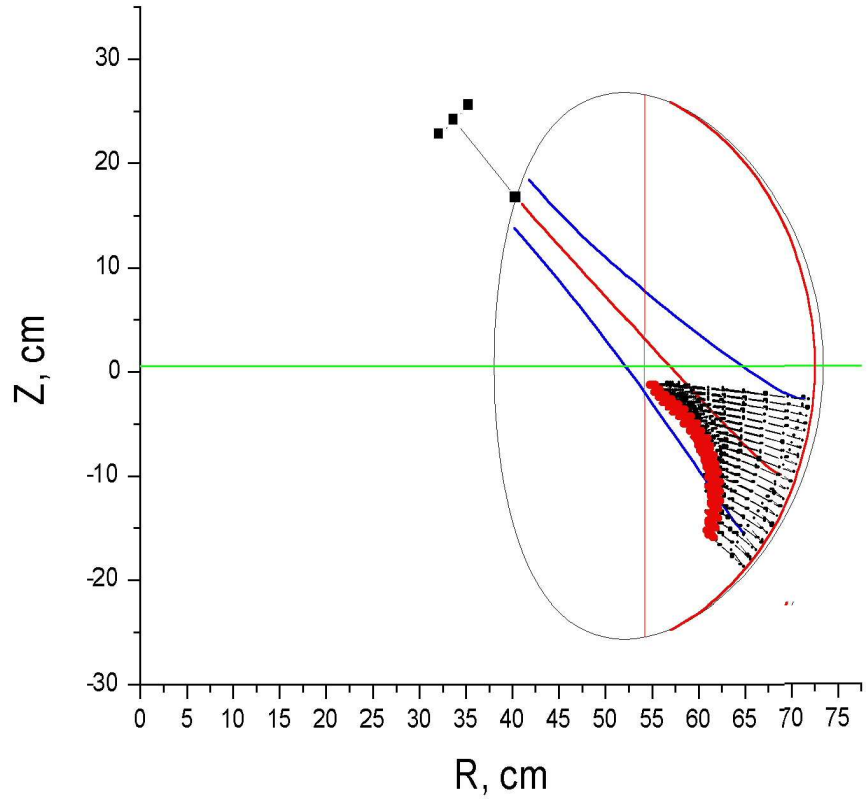
Virtual Beam Tracing Results



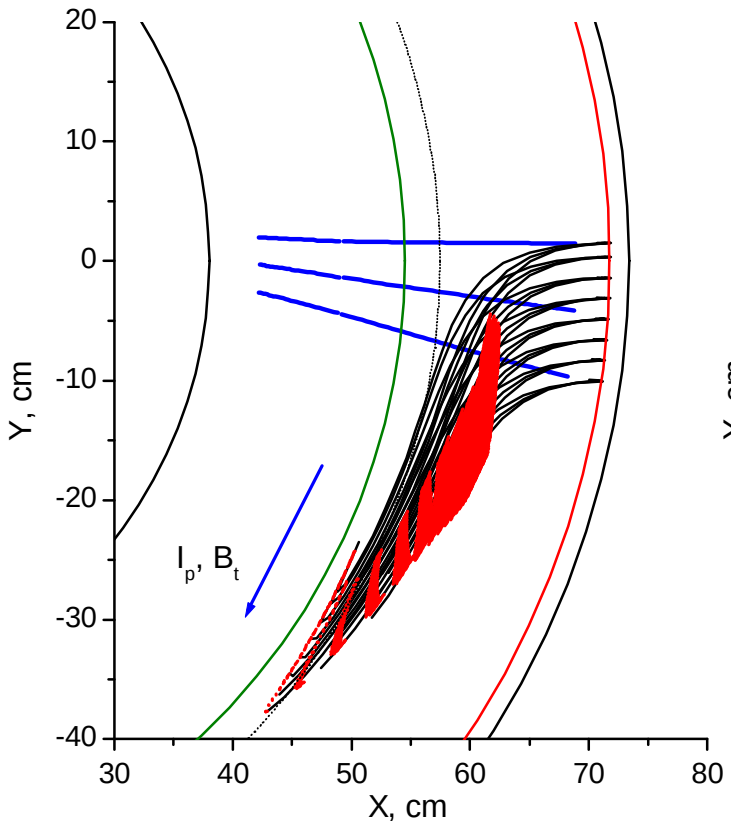
Poloidal projection of EBW beam tracing results for negative toroidal launch angle of -16.7º



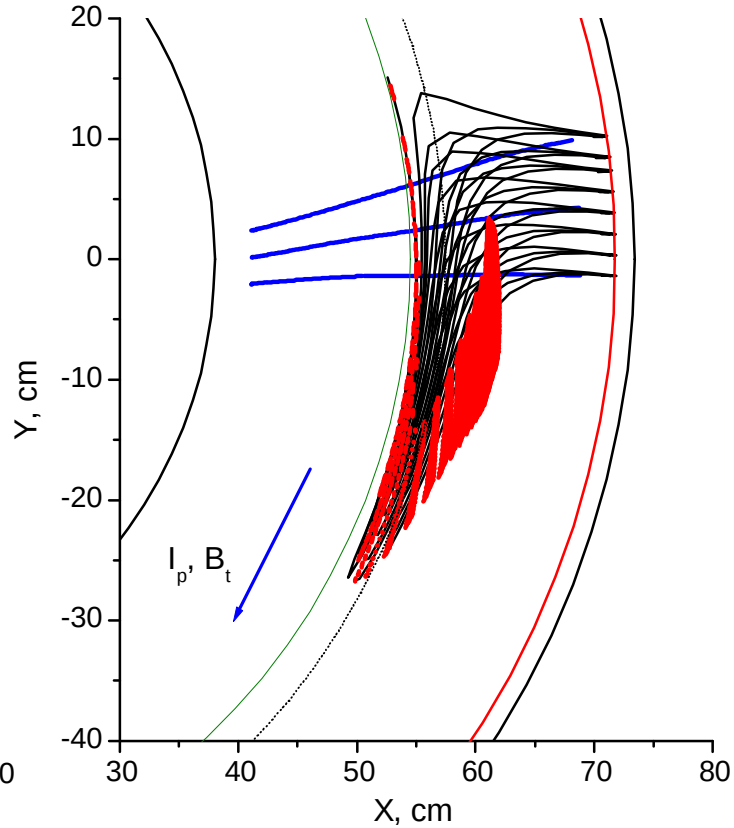
Poloidal projection of EBW beam tracing results for positive toroidal launch angle of +16.7º

With the existing antenna set-up the EBW power deposition profile is located well below the midplane for all negative and positive launch angles

Virtual Beam Tracing Results



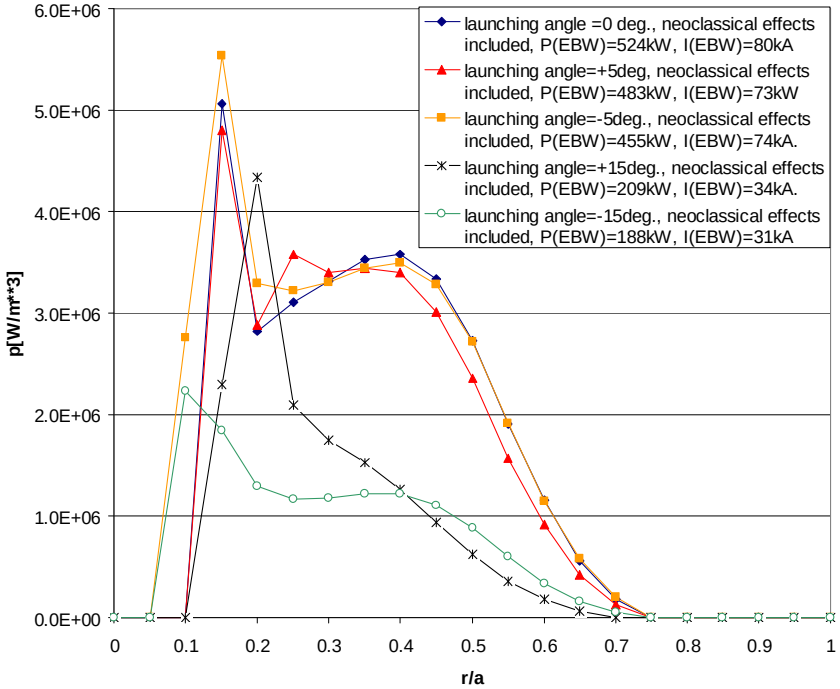
Toroidal projection of EBW beam tracing results for negative toroidal launch angle of -16.7º



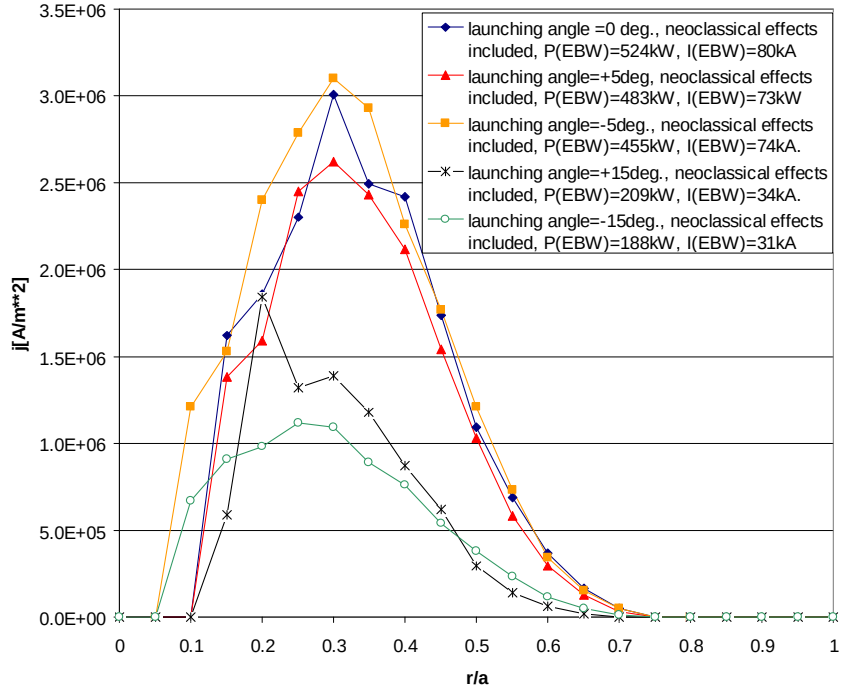
Toroidal projection of EBW beam tracing results for positive toroidal launch angle of +16.7º

At the absorption region EBWs have predominantly positive $k_{||}$ for all negative and positive launch angles

EBW heating and CD modelling

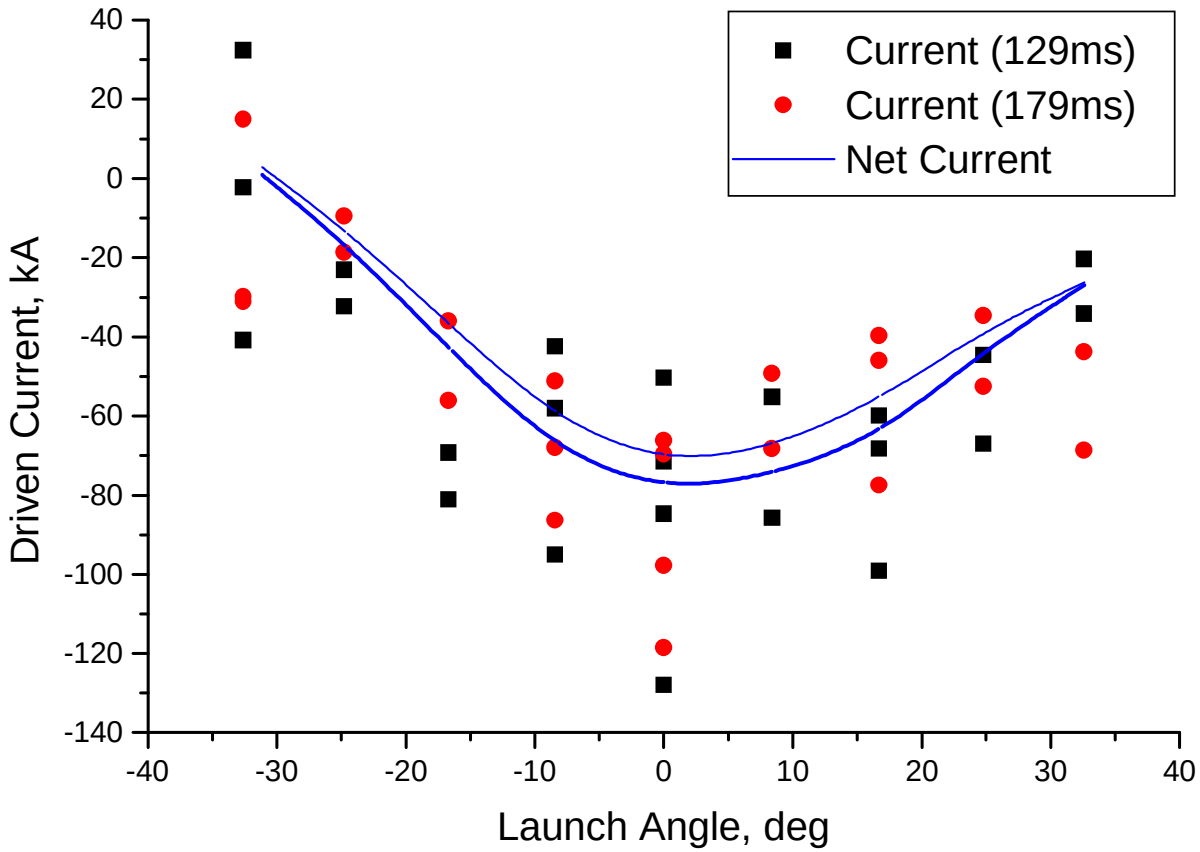


EBW power deposition profiles for different toroidal launch angles



EBW driven current density profiles for different toroidal launch angles

EBW modelling results



EBW beam tracing results for currents driven by ECRH and experimental results

- **Fokker-Planck codes include trapping effects. Without trapping, codes predict almost twice higher EBW driven current**

- **The sign of the EBW driven current does not depend on the toroidal launch angle. The current is always in the counter-direction**

Summary

- It was found that the heating efficiency with the EBW-mode is much higher than with the X1-mode alone

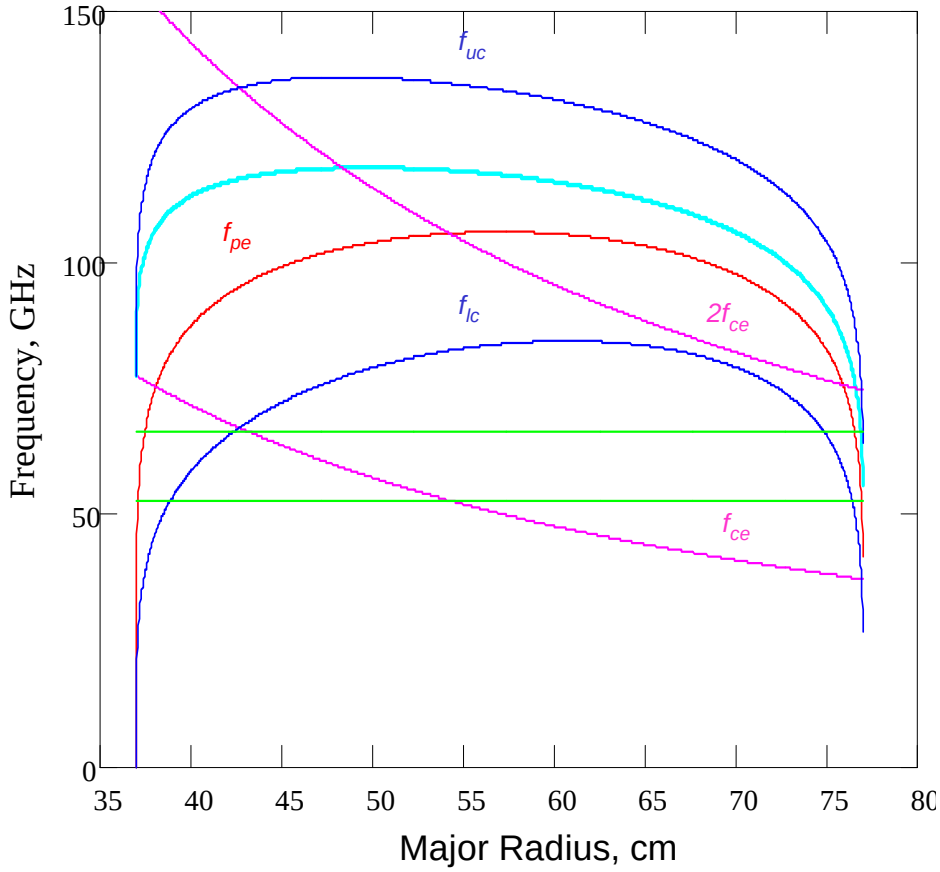
- From the plasma power balance the EBW driven current has been found to be in the counter direction for all launch angles with the maximum of ~100 kA and current drive efficiency $\eta_{20} = n_{e20} R I_{CD} / P_{RF} \cong 0.035$ (10^{20} A/W m^2)

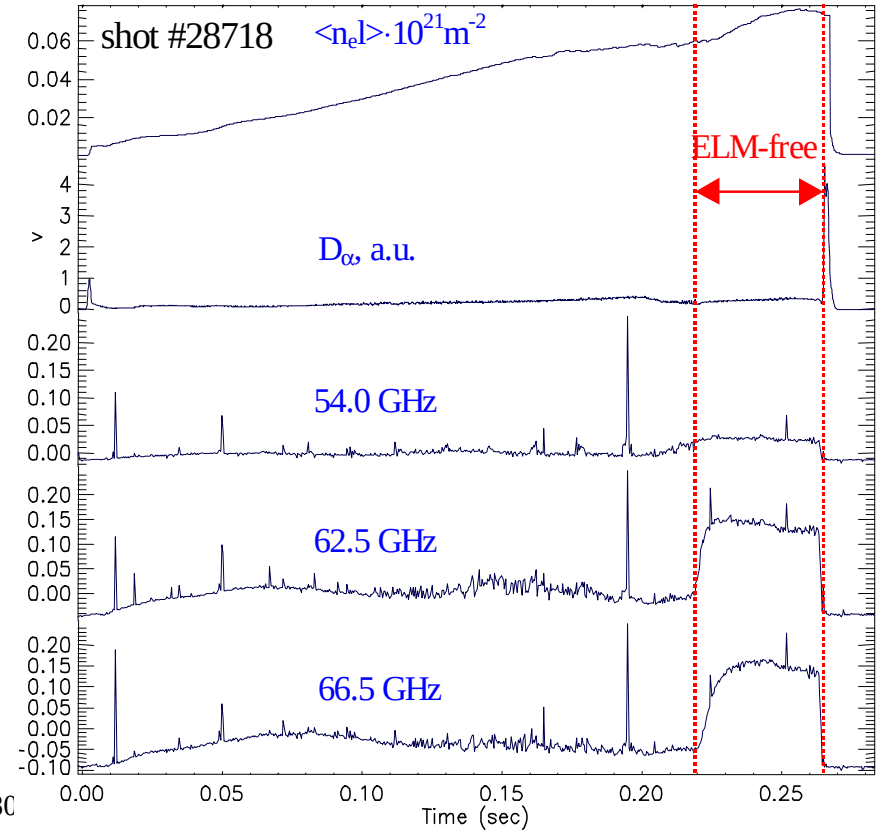
- Beam tracing simulation along with 2D-Relativistic Fokker-Plank codes predict EBW driven current in the counter-direction with the maximum in the range of 72-80 kA, which is consistent with experimental results

- For the existing antenna configuration in COMPASS-D the EBW driven current is always directed in the counter-direction to the plasma current independent of the launch angle and the direction of the plasma current

- The direction of the driven current can be changed from counter- to co- if the EBW is absorbed predominantly above the midplane

EBW emission in COMPASS-D

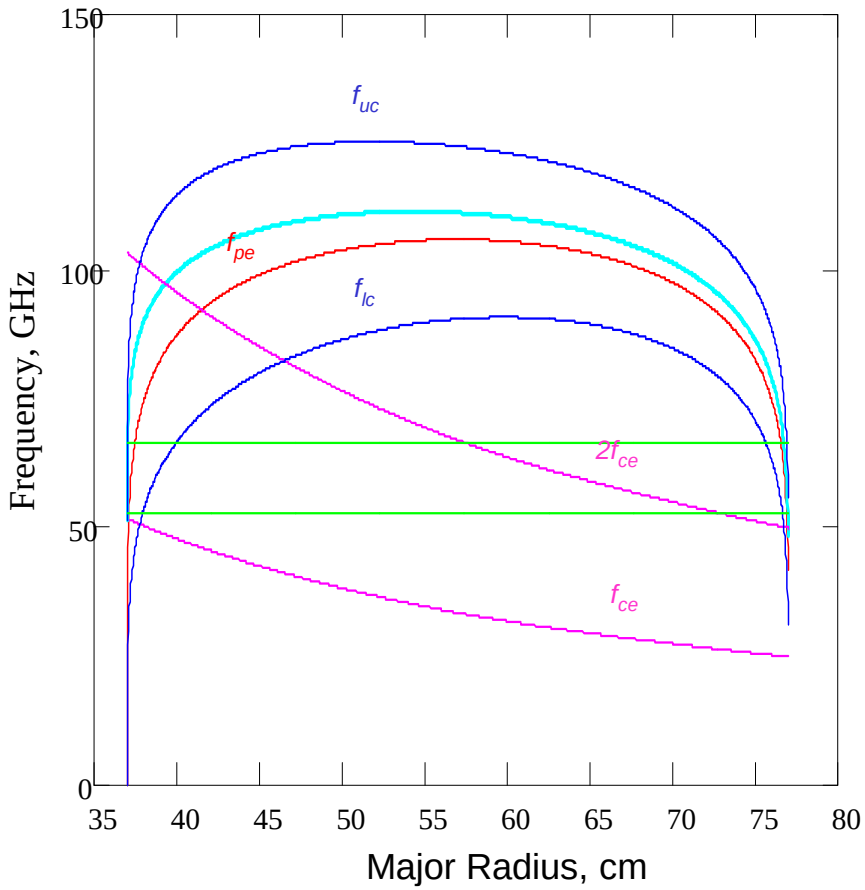




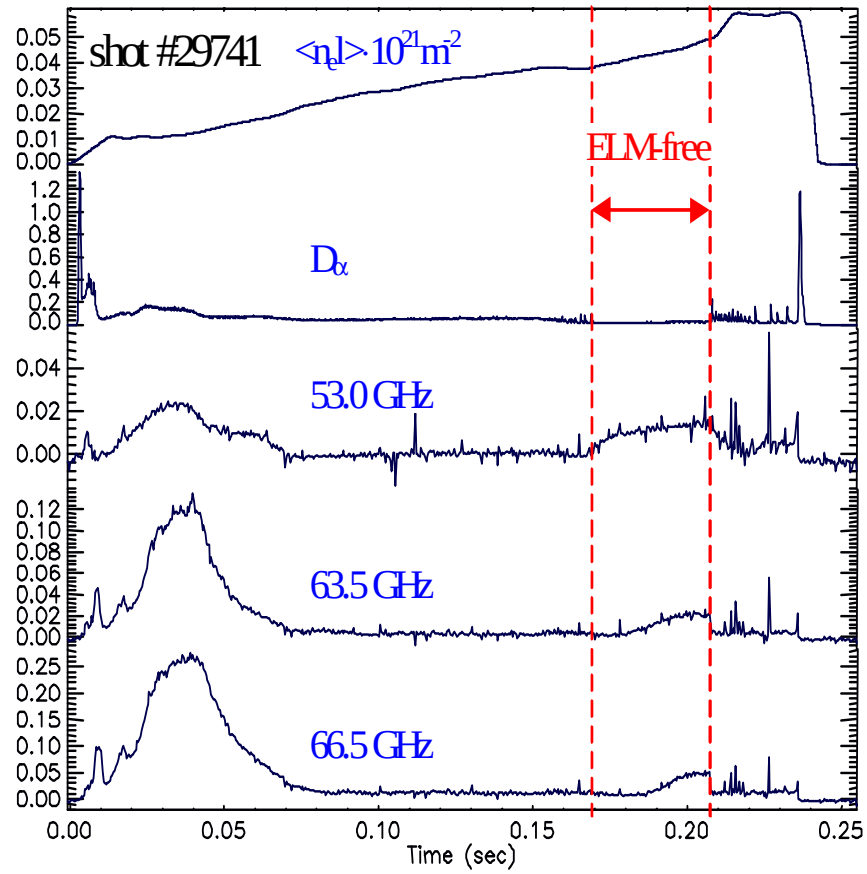
Cut-offs and resonances in COMPASS-D during H-mode, B_0 = 1.8T, n_{e0} = 1.4·10^{20}m^{-3}

EBW emission from fundamental ω_{ce} resonance during H-mode, B_0 = 1.8T

EBW emission in COMPASS-D



Cut-offs and resonances in COMPASS-D during H-mode, B_0 = 1.2T, n_{e0} = 1.4·10^{20}m^{-3}



EBW emission from $2\omega_{ce}$ resonance during H-mode, B_0 = 1.2T

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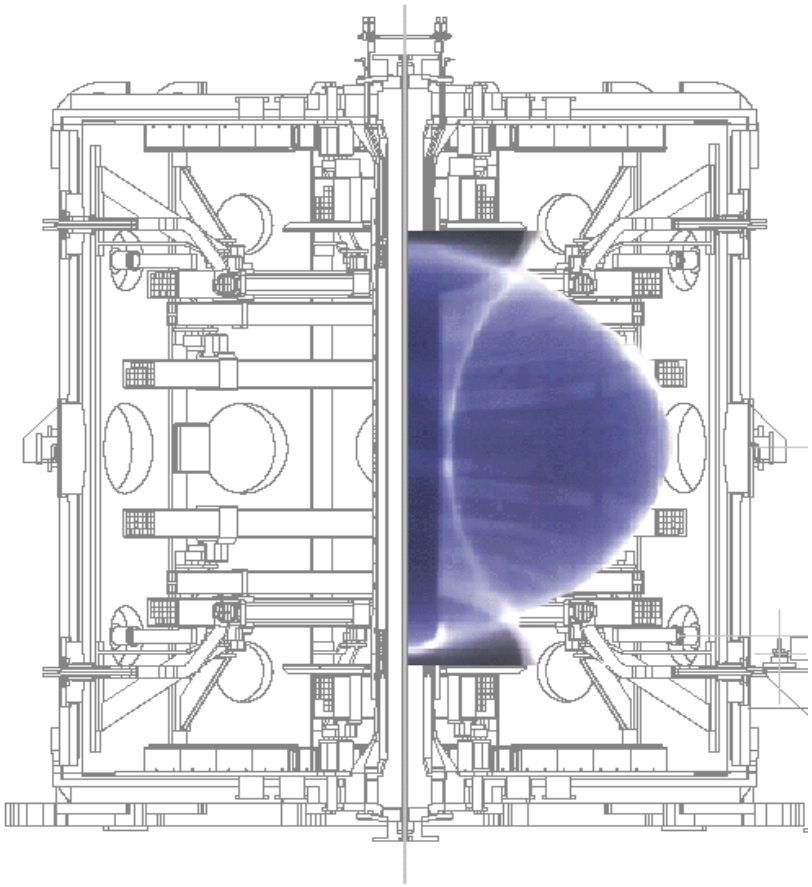
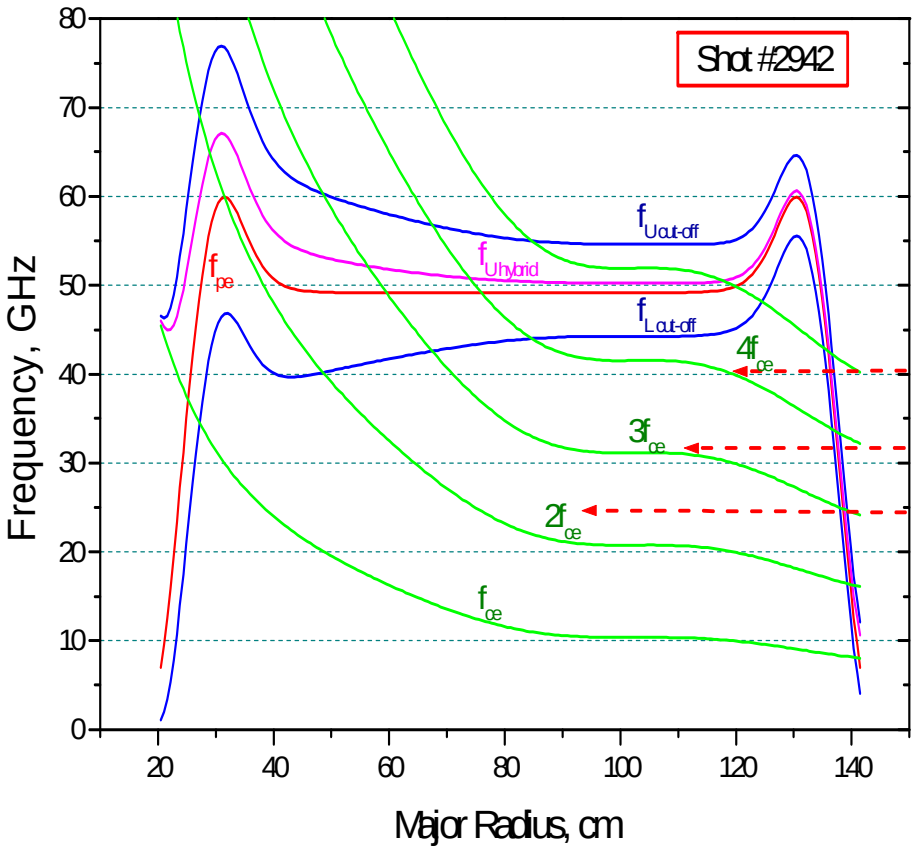
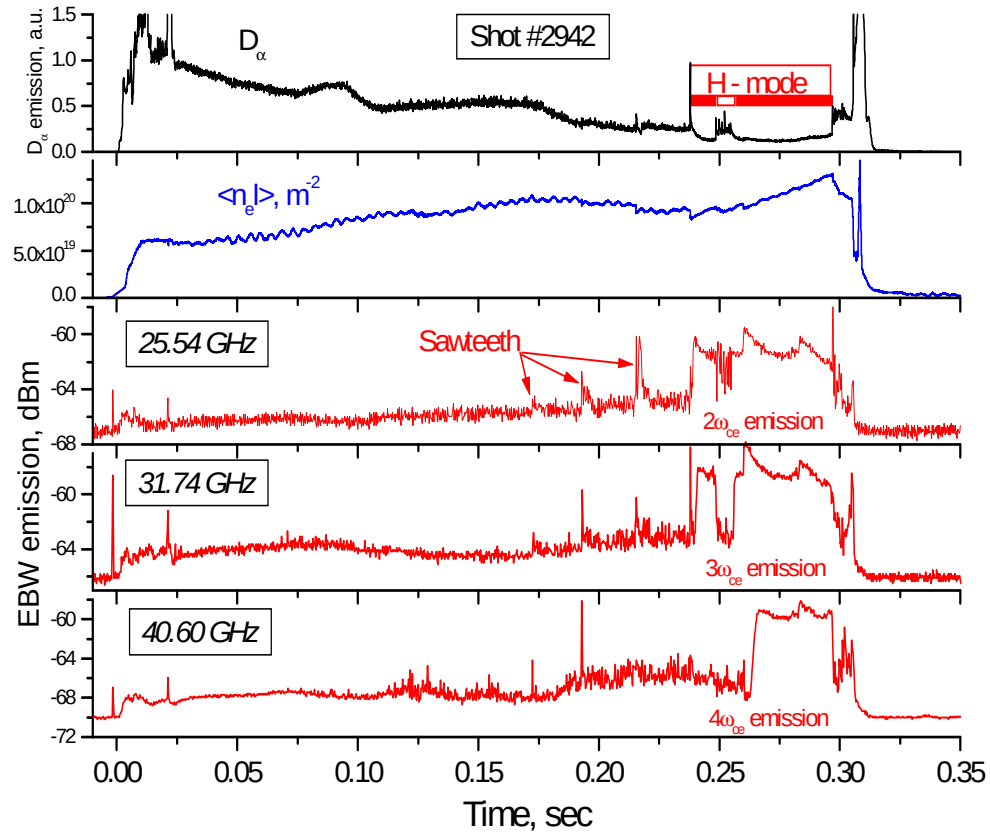
MAST Parameters



	Design	Achieved
Major radius	0.85 m	0.85 m
Minor radius	0.65 m	0.65 m
Elongation	≥2.0	2.45
Aspect Ratio	≥1.3	1.3
Plasma current	2 MA	1.3 MA
Toroidal field	0.52 T	0.52 T
NBI heating	5 MW	3.0 MW
RF heating	1.4 MW	0.9 MW
Pulse length	5 s	0.7 s

EBW emission in MAST





Midplane topology of cut-offs and resonances during H-mode in MAST

EBW signals from different EC harmonics during H-mode in MAST

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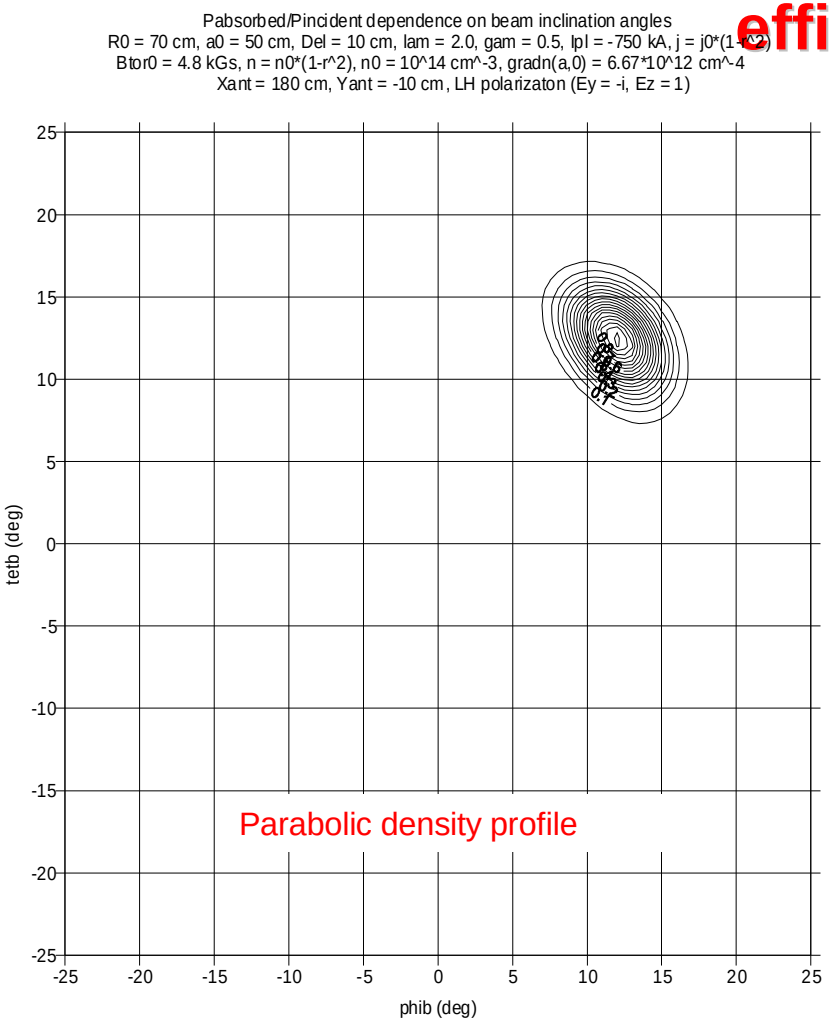
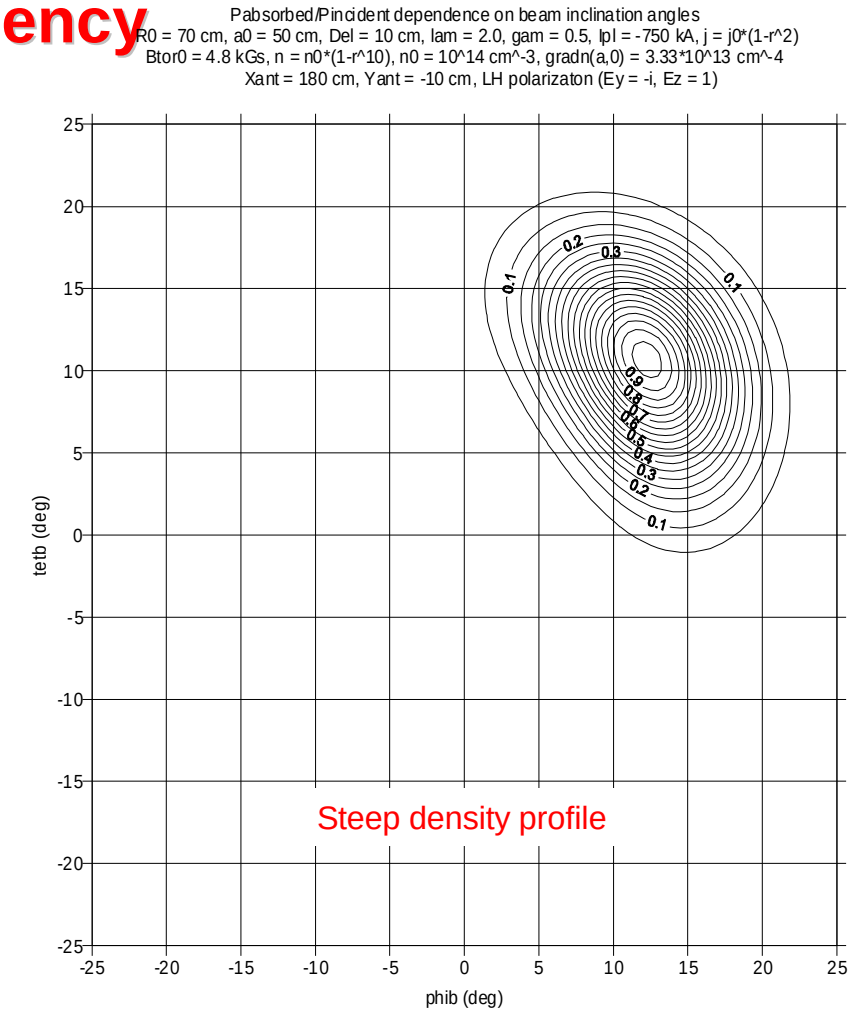
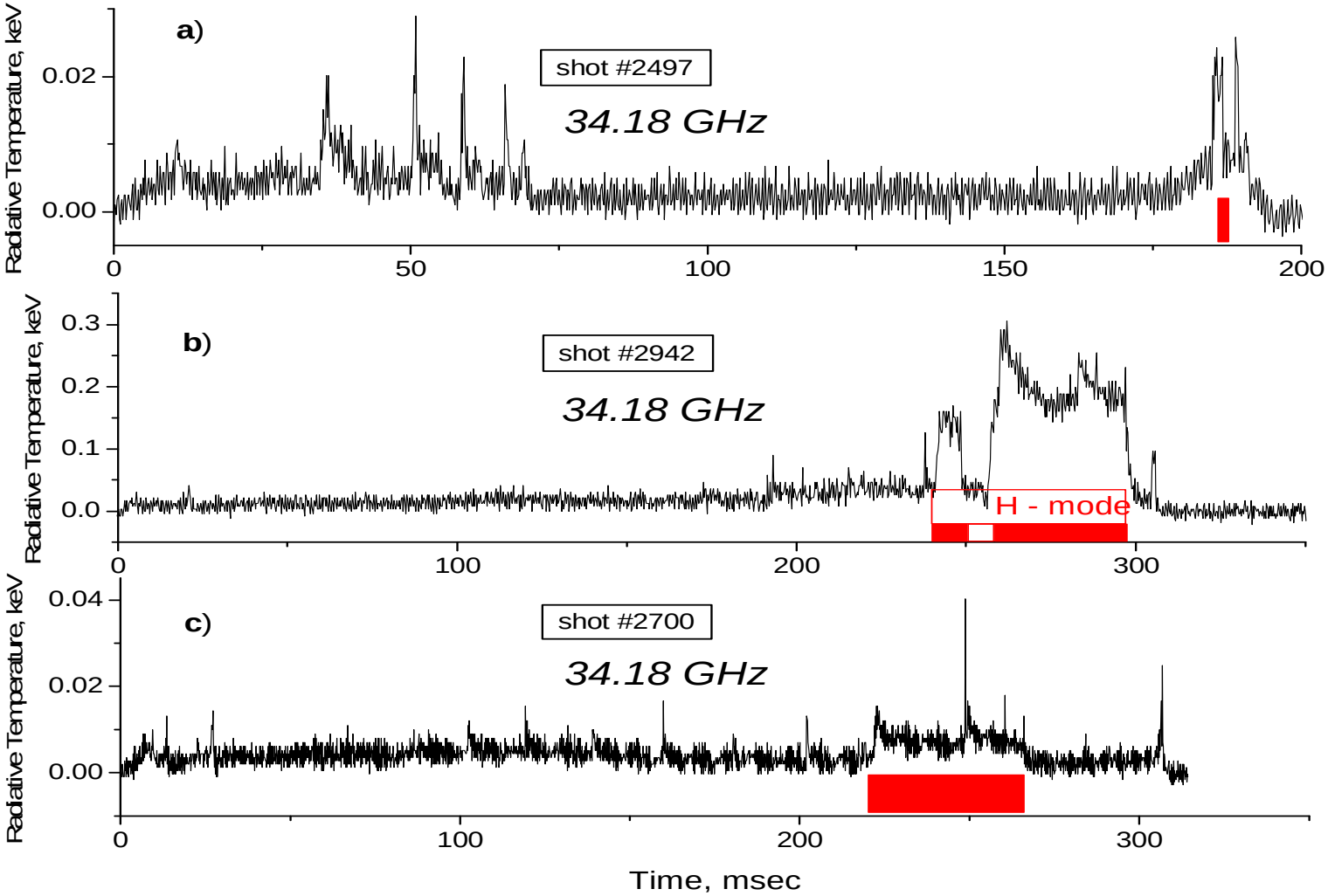
O-X-B mode conversion efficiency





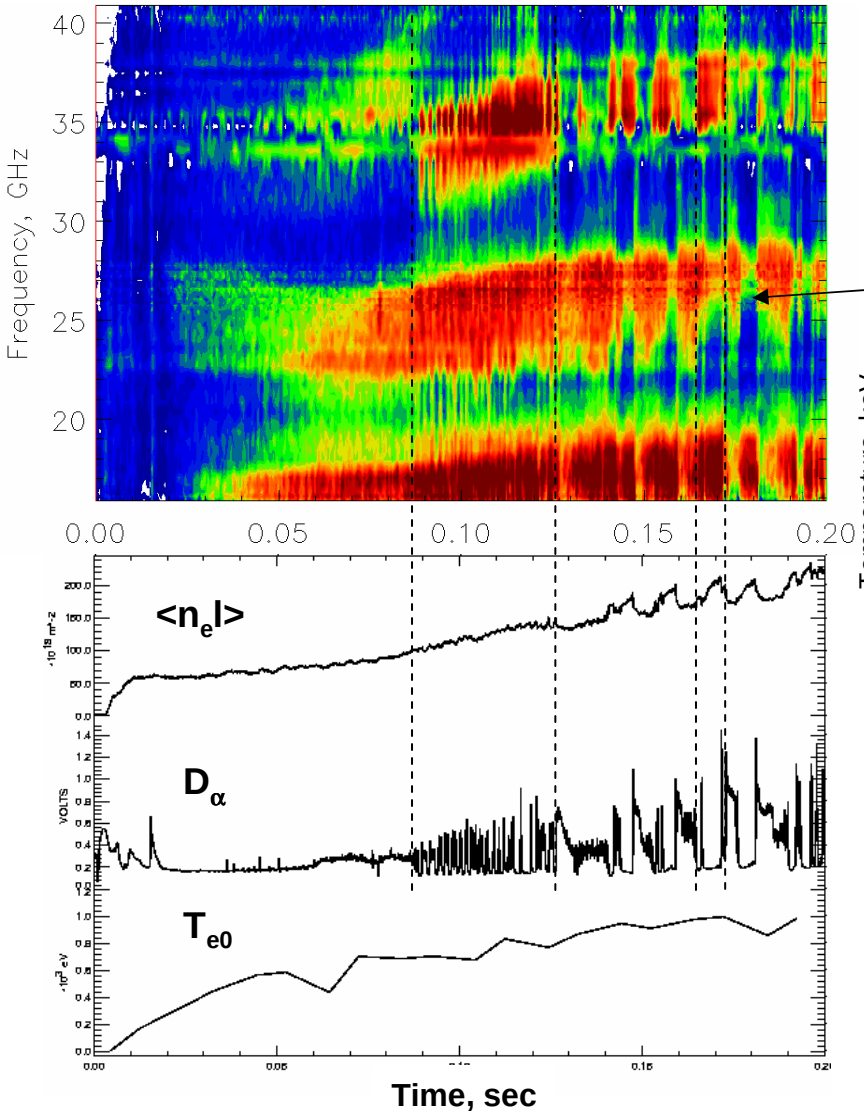
Contour plot of the O-X-B mode conversion efficiency represented in angular co-ordinates.
Tetb angle (elevation) is measured upward in the poloidal direction.
Phib angle (azimuth) is measured clockwise in the toroidal direction.

EBW emission in MAST



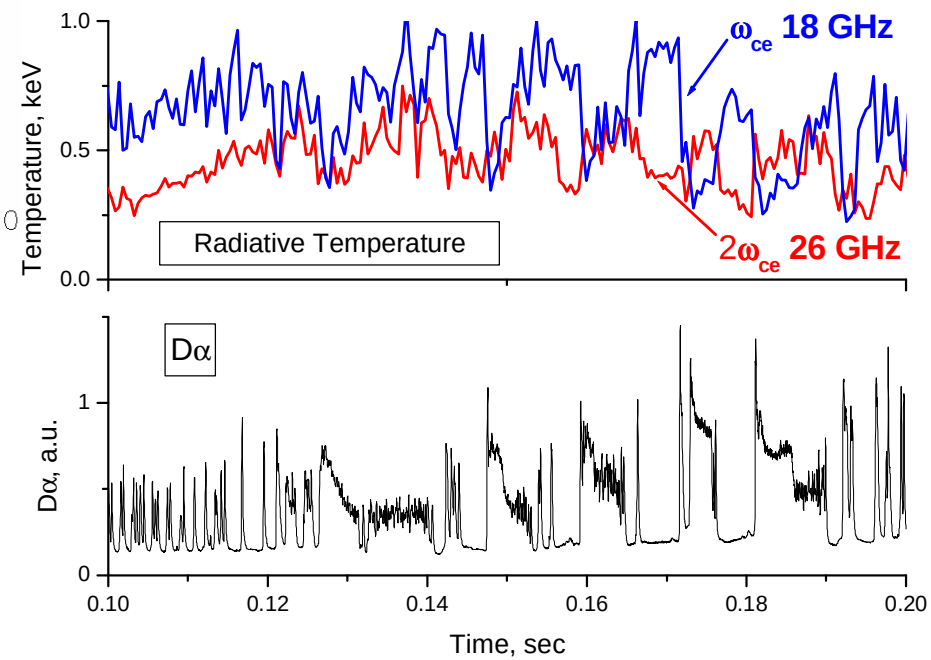
Radiometer signals during H-mode for different viewing angles:
a) perpendicular X-mode, b) close to the optimum for B-X-O conversion,
c) optimum for opposite current

EBW emission in MAST



Shot #7695 EBW spectrum measured during H-mode in low TF (I_{TF} =77 kA)

Inverted ELM modulation



See also J. Preinhaelter's poster on Ray-tracing modelling of the EBW emission in MAST

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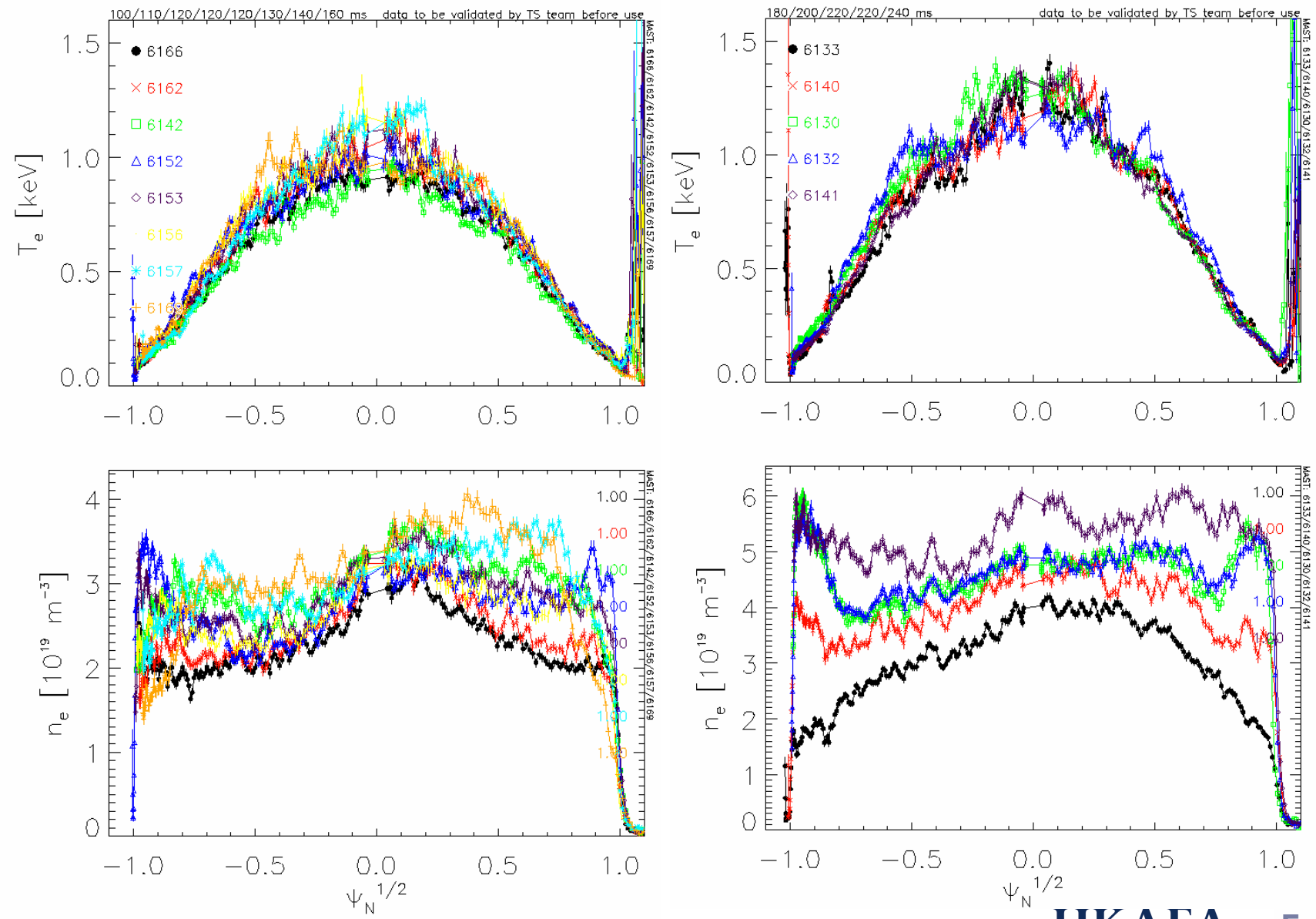
EBW Scenario Development



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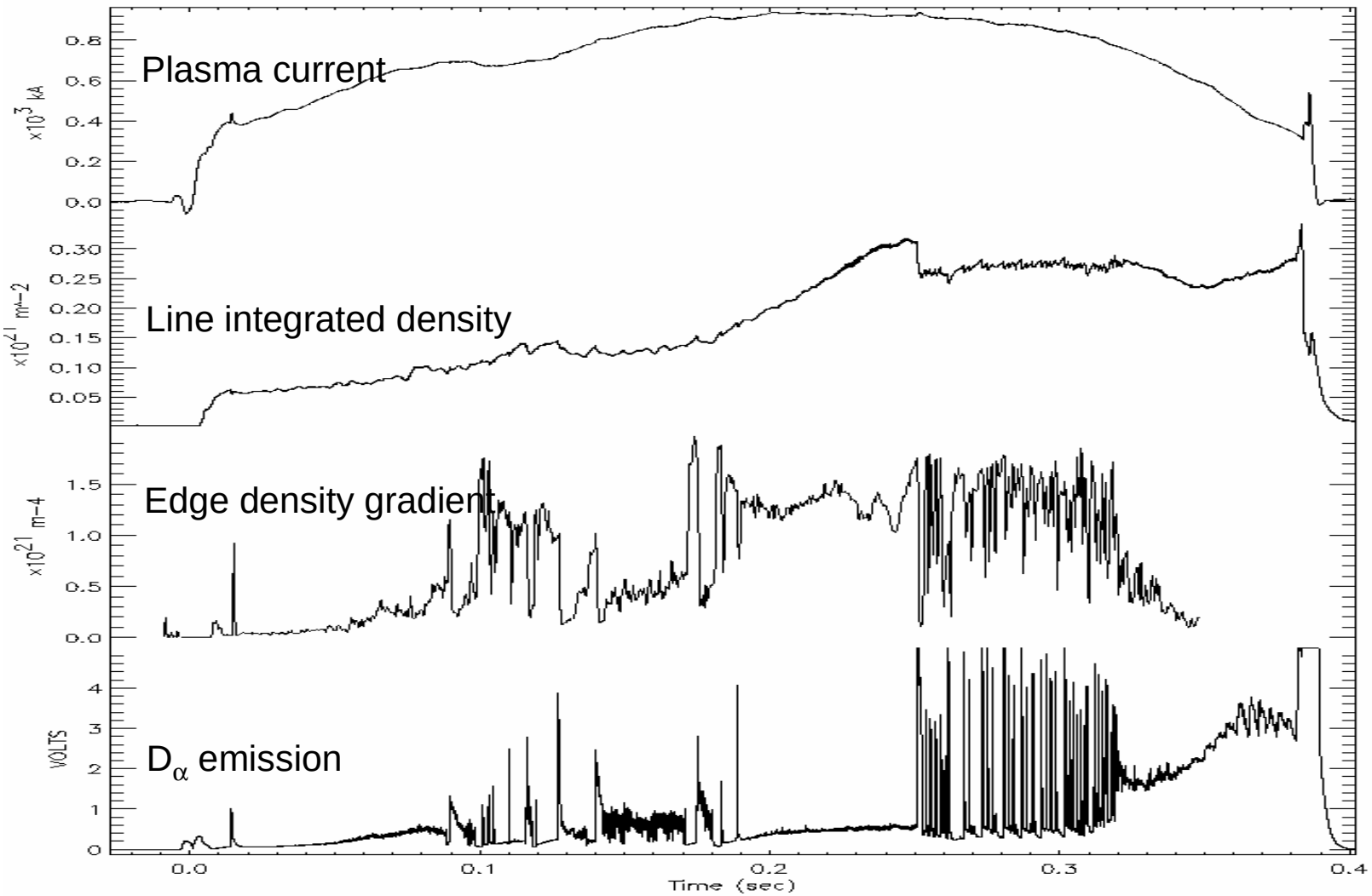
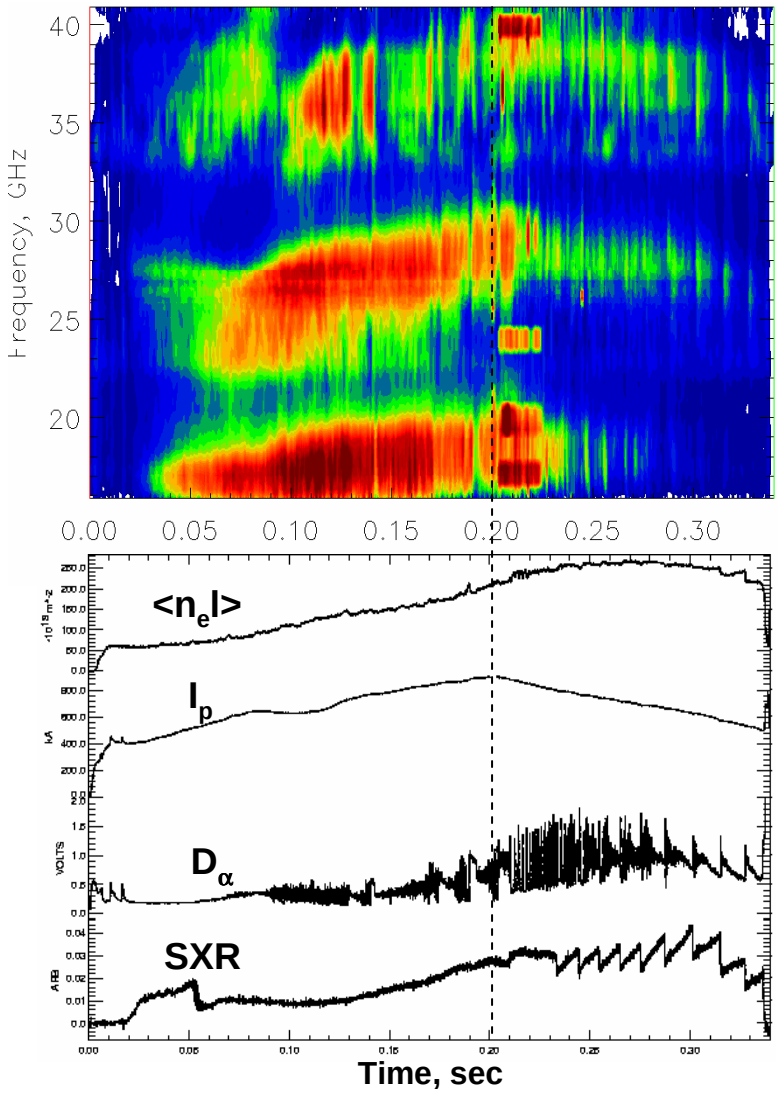
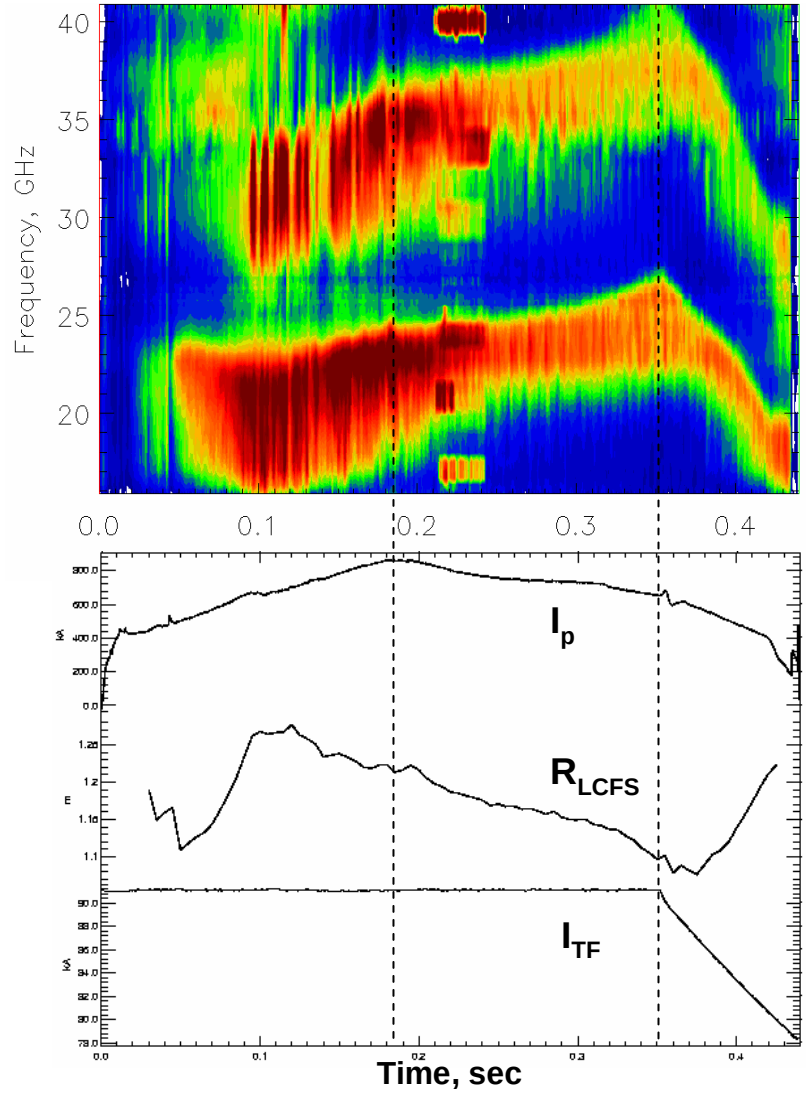
V Shevchenko, *Seminar at PPPL 16 May 2003, Princeton, USA*

EBW Scenario Development



EBW emission in MAST

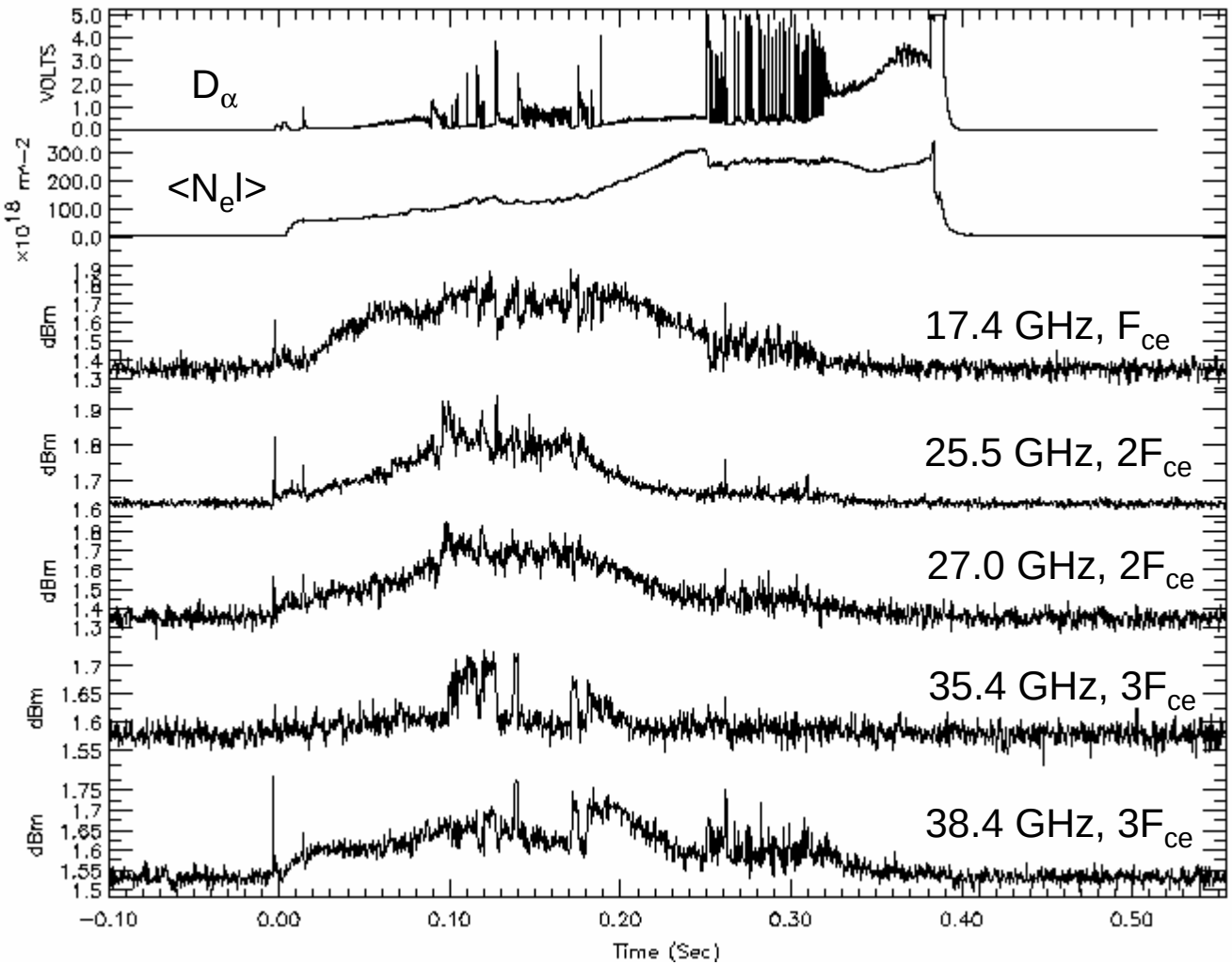




Shot #7680 EBW spectrum in low TF (I_{TF} =77 kA) with the plasma current ramp down

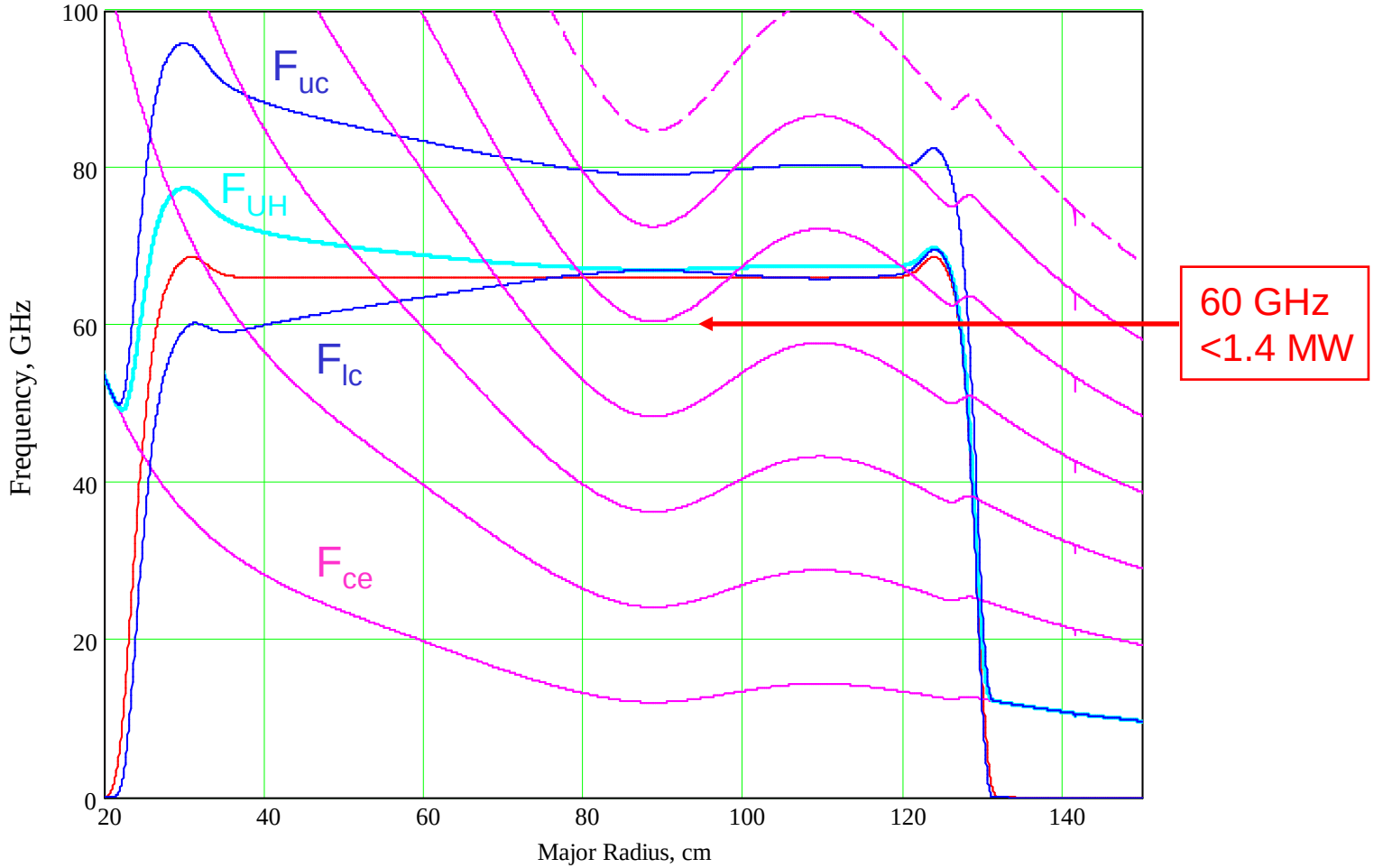
Shot #7798 EBW spectrum measured during H-mode in high TF (I_{TF} =92 kA)

EBW emission during high density H-mode



EBW signals degradation during high density H-mode in MAST

EBW heating in MAST



Midplane topology of cut-offs and resonances in target shot for EBW heating in MAST

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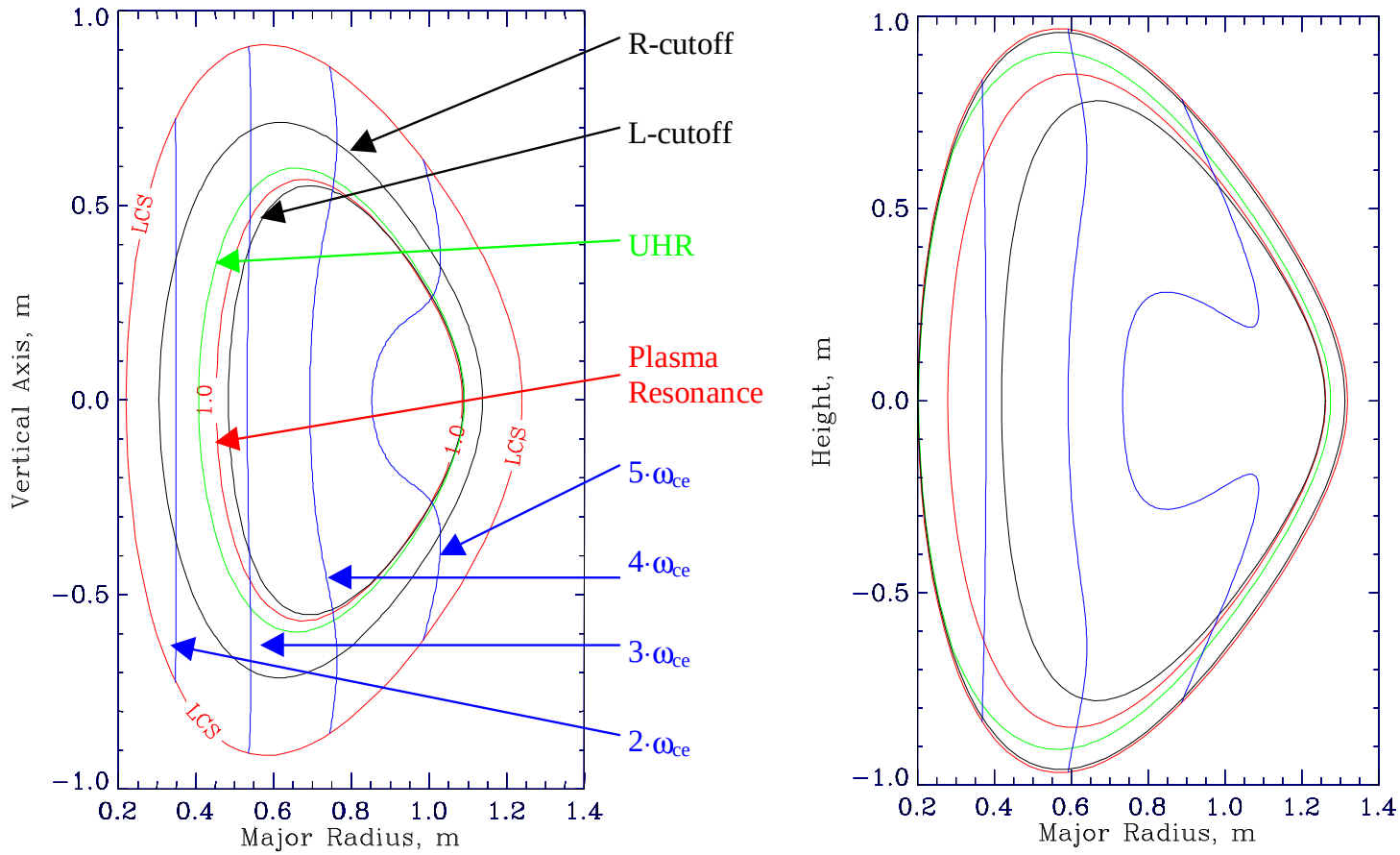
EBW Heating on MAST



Cross-section of cut-offs and resonances in MAST for 60 GHz launched at optimal angle

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EBW emission results

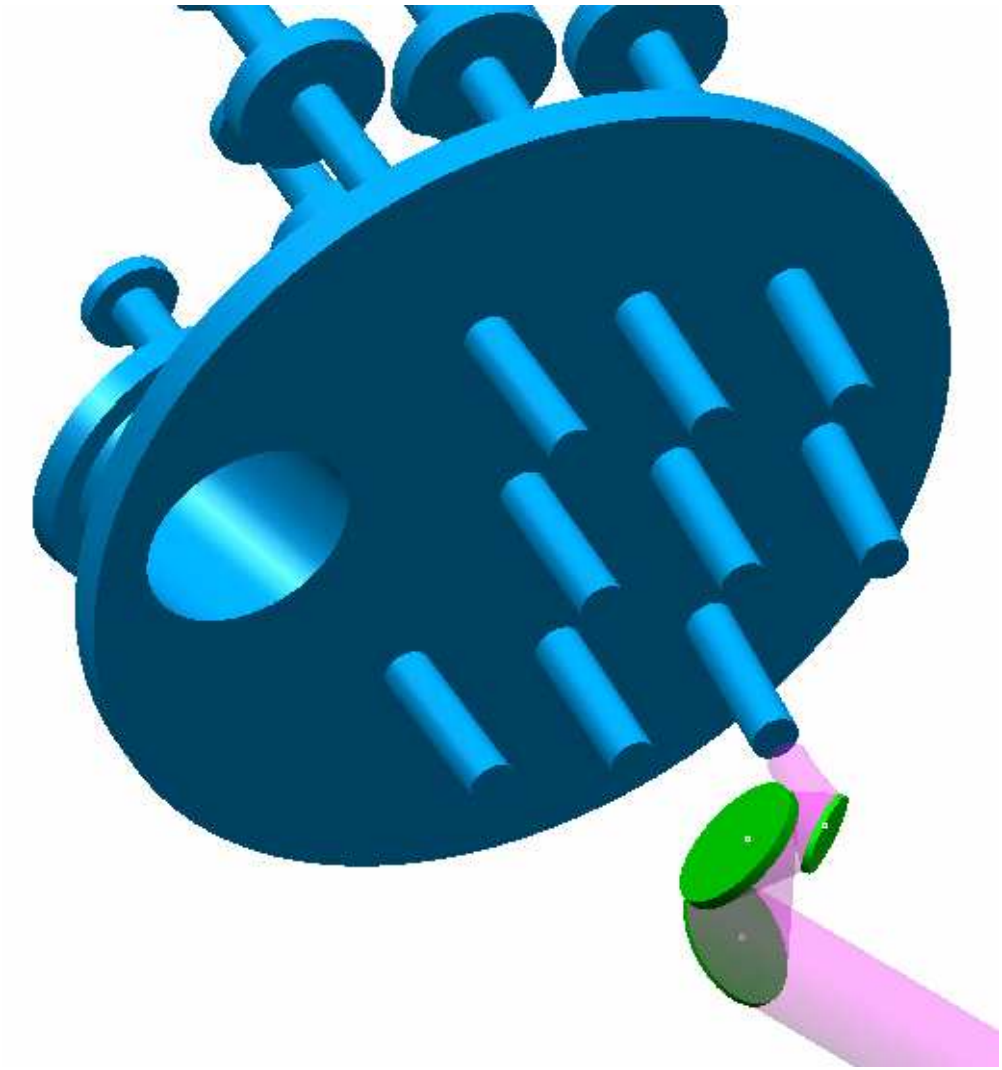
- In high density and high current H-mode plasmas the ELM modulation behaviour of EBW emission can be inverted at some harmonics.

- In high density and high current H-mode plasmas the EBW emission intensity decays with the time scale of ~20- 30 ms.

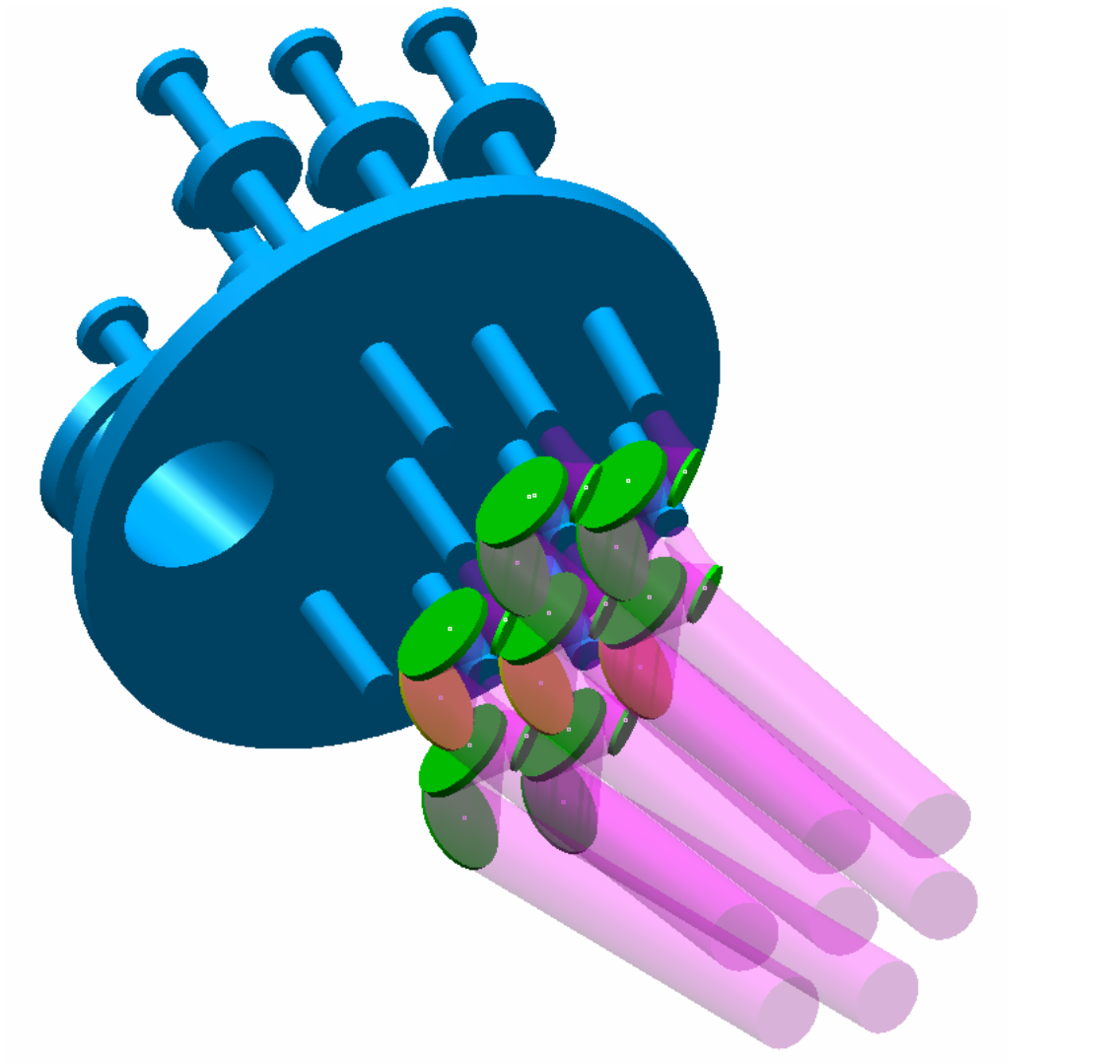
- These unusual effects are less pronounced at high TF. They can be reduced or totally suppressed by plasma current ramp up and by plasma compression. Emission also can come back to 'normal' after the giant ELM or IRE.

- Apparently, these effects can be attributed to the plasma current redistribution initiated by the H-mode. This could produce local magnetic field inhomogeneity in the gradient zone, which has a dramatic effect on the EBW ray trajectories.

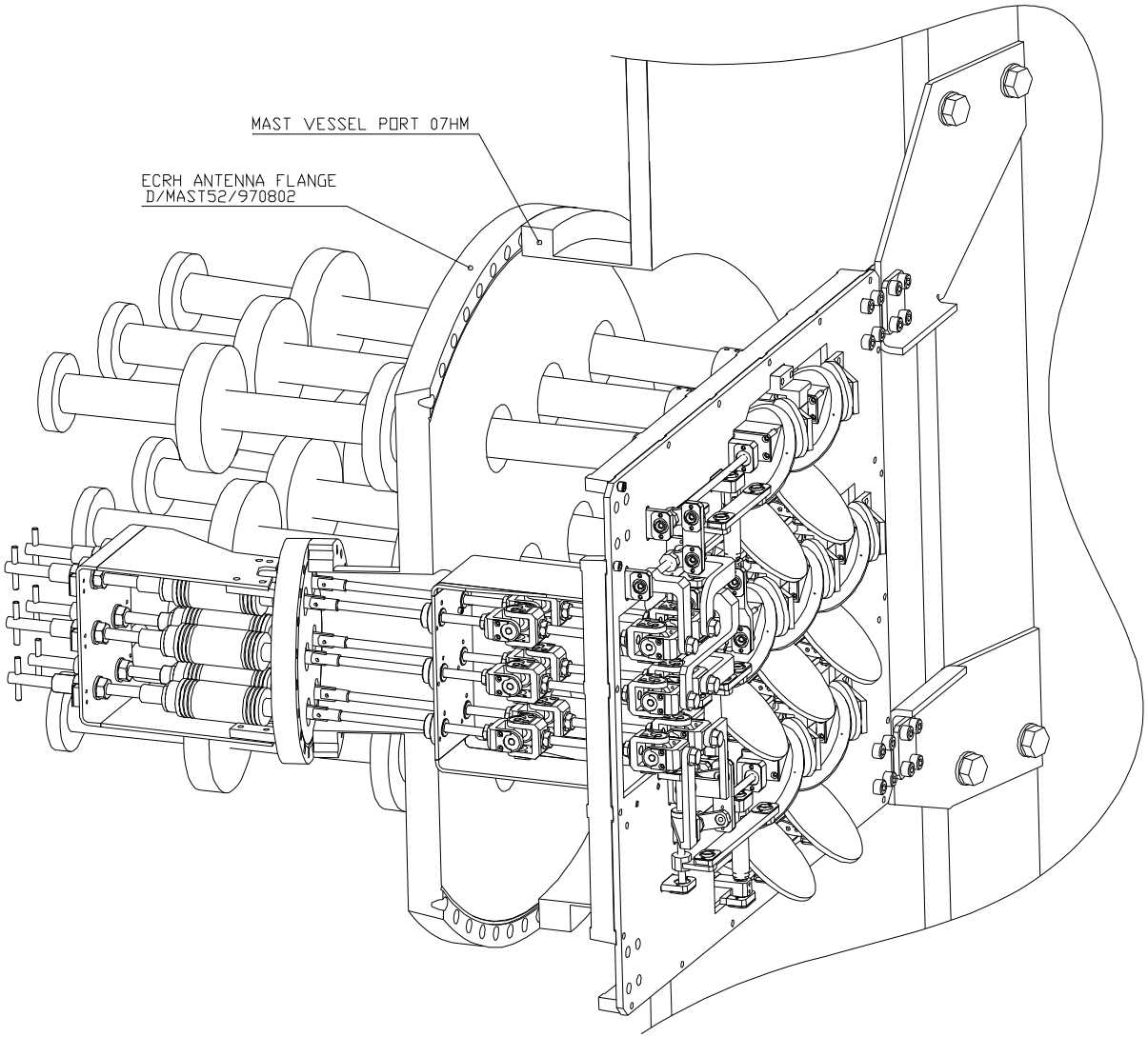
Quasioptical components of the EBW Launcher



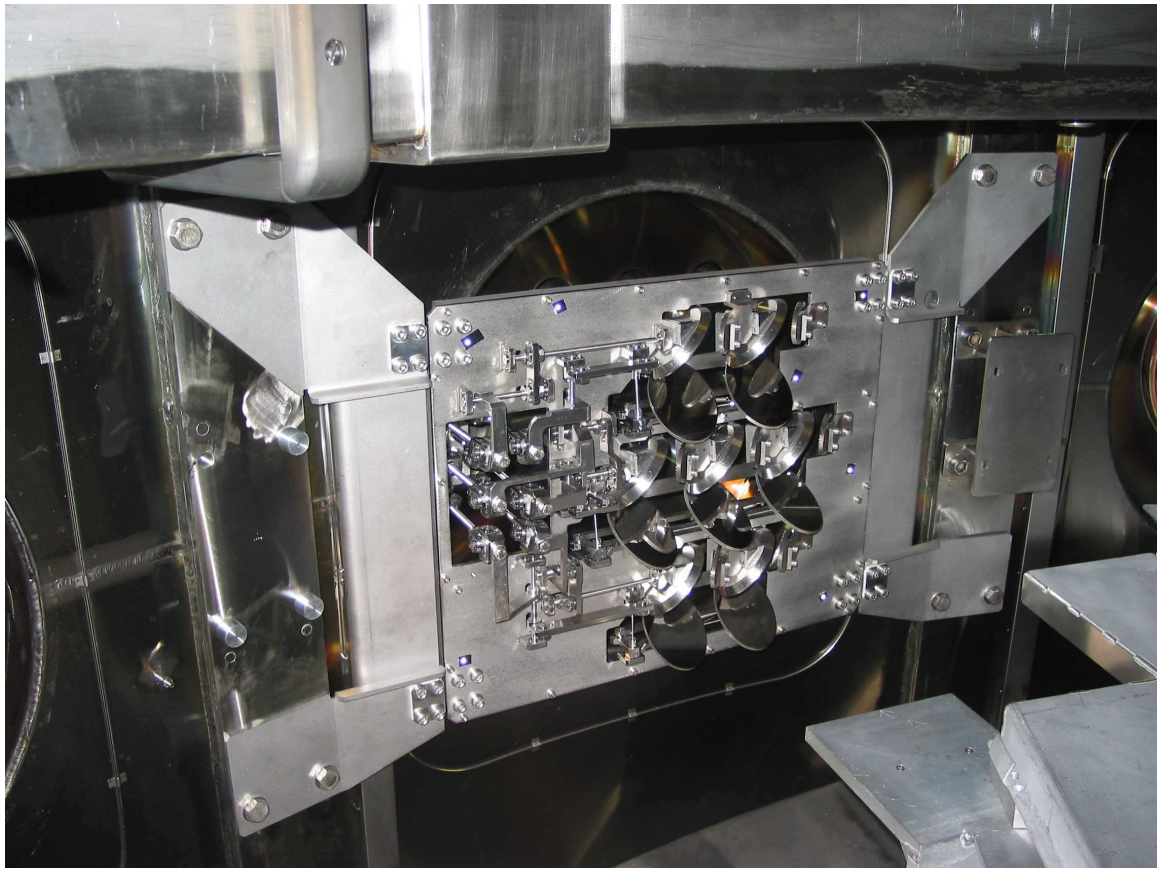
EBW Launcher in MAST



EBW Steerable Launcher for MAST

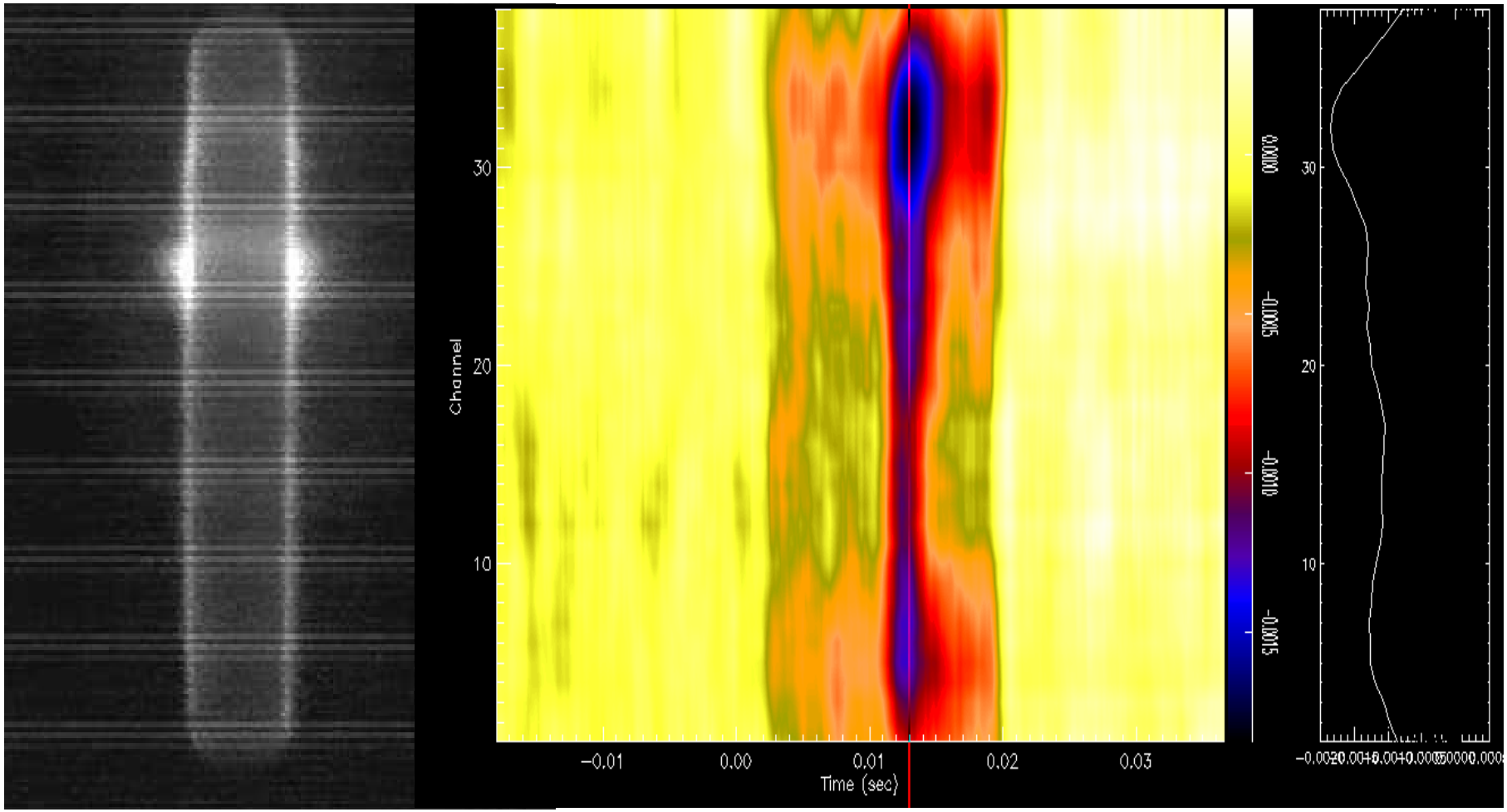


EBW Steerable Launcher in MAST



- Final polarisation can be chosen from linear to circular
- Resultant beam divergency is less than +/-2.5^o (ω = 25 mm)
- Beams are grouped by the poloidal position 2-3-2
- Each group has a united remote control for poloidal and toroidal steering
- Poloidal steering range of +/-13°, toroidal +/-24°, accuracy of 0.5^o

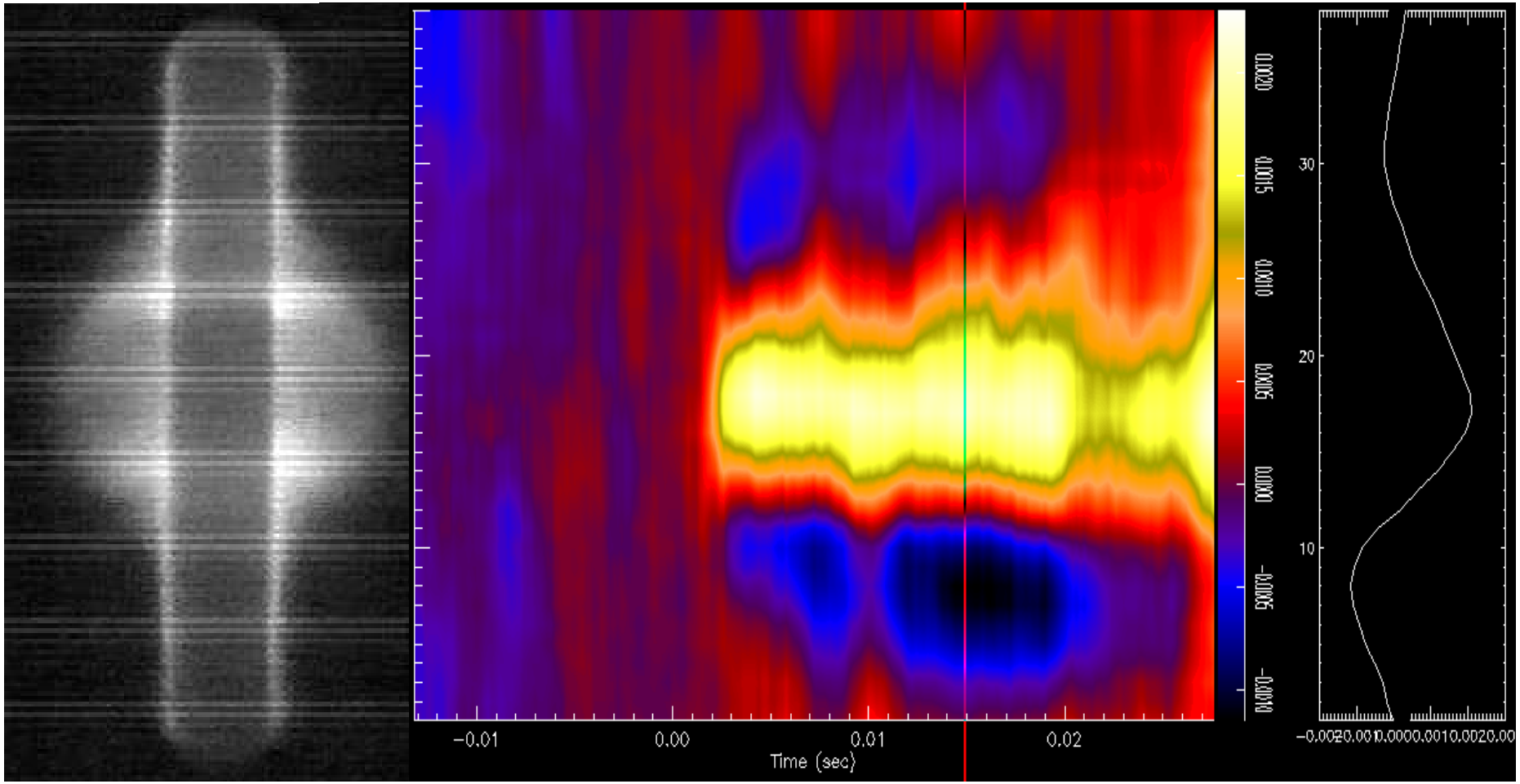
ECRH Breakdown in TF only



CCD image of the ECRH breakdown phase at ω_{ce} in a pure toroidal magnetic field

Vertical magnetic field induced by plasma during ECRH breakdown. ECRH pulse of 20 ms (0.3 MW), O-mode polarisation.

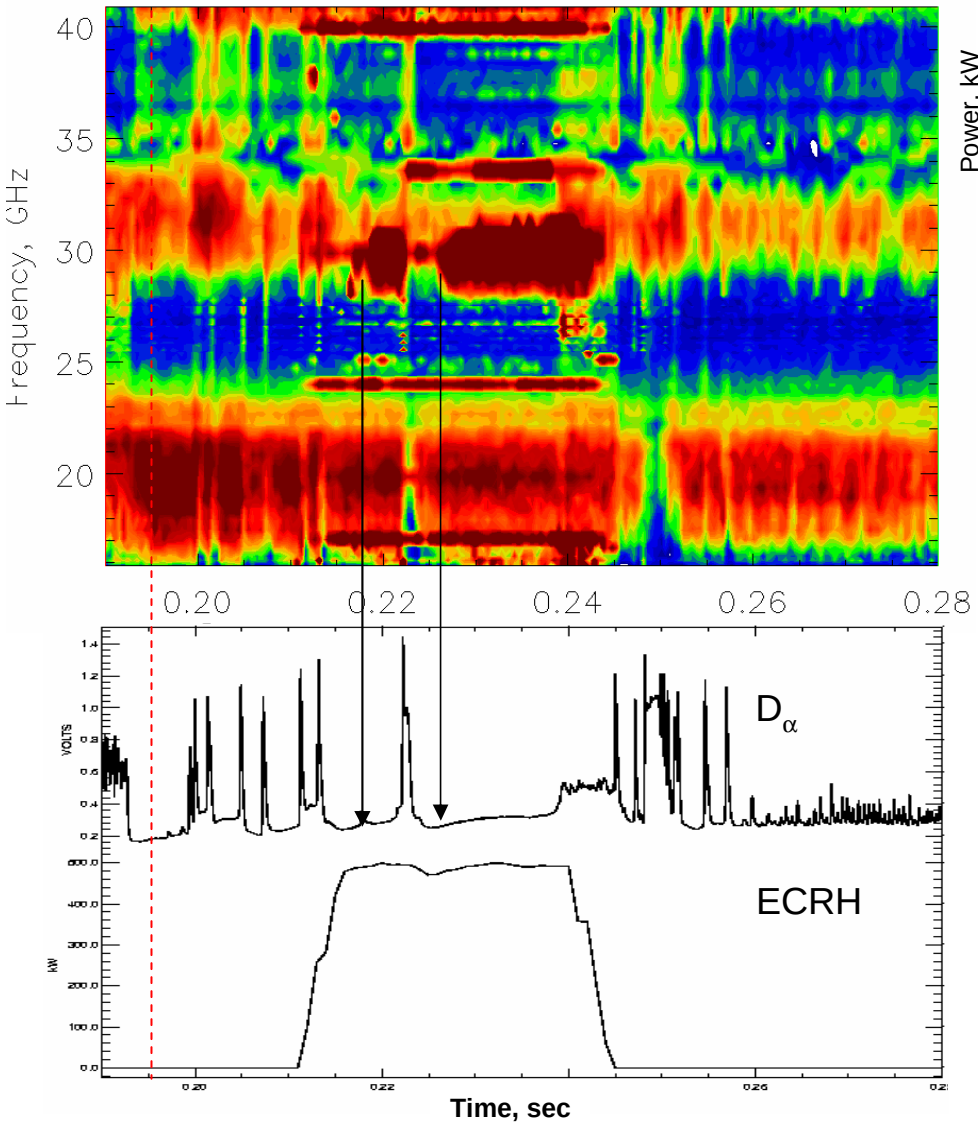
ECRH Breakdown in TF and Small Vertical Field



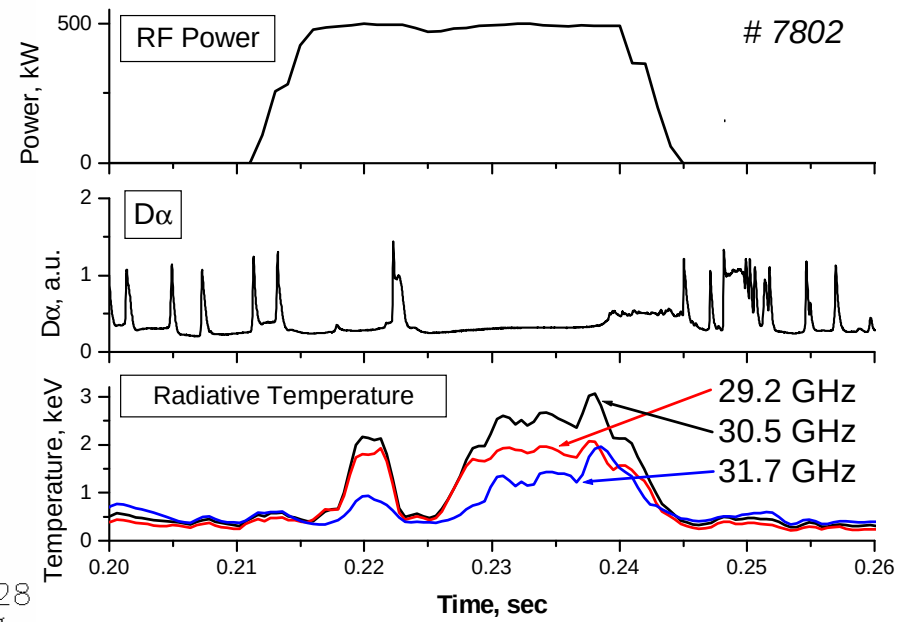
CCD image of the ECRH breakdown phase in toroidal and 5 mT vertical magnetic field

Vertical magnetic field induced by plasma during ECRH breakdown. ECRH pulse of 20 ms (0.3 MW), O-mode polarisation.

O-X-B heating heating in MAST



EBW emission from ω_{ce} and $2\omega_{ce}$ harmonics during ECRH



EBW emission during ECRH pulse in ELM-free phase

- **Radiative temperature exceeds T_e during ECRH pulse**
- **Radiative temperature increase due to EBWH is always delayed by ~5 ms from the ELM**
- **TS shows broadening of the scattered spectra at major radii corresponding to EBW power deposition**

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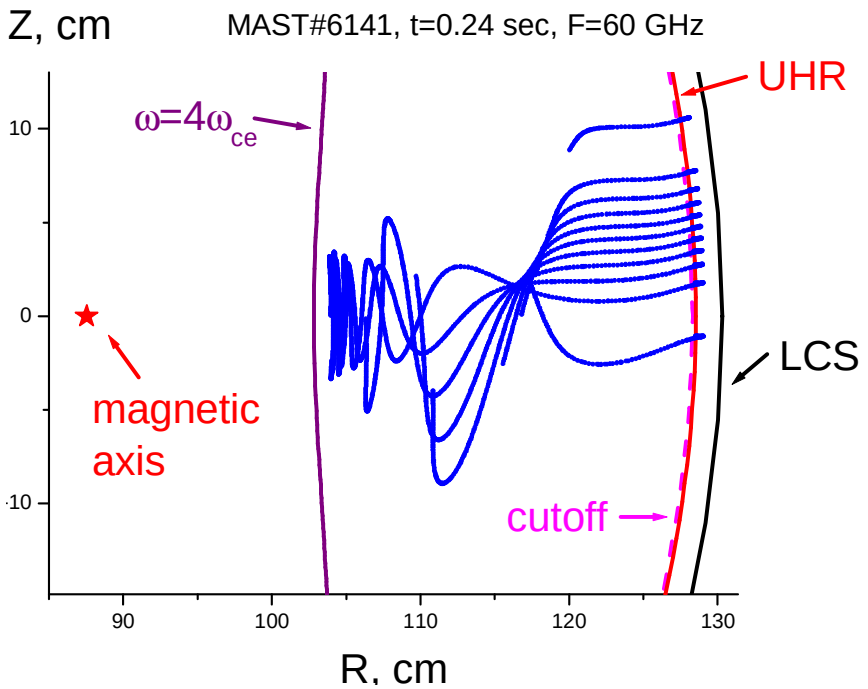
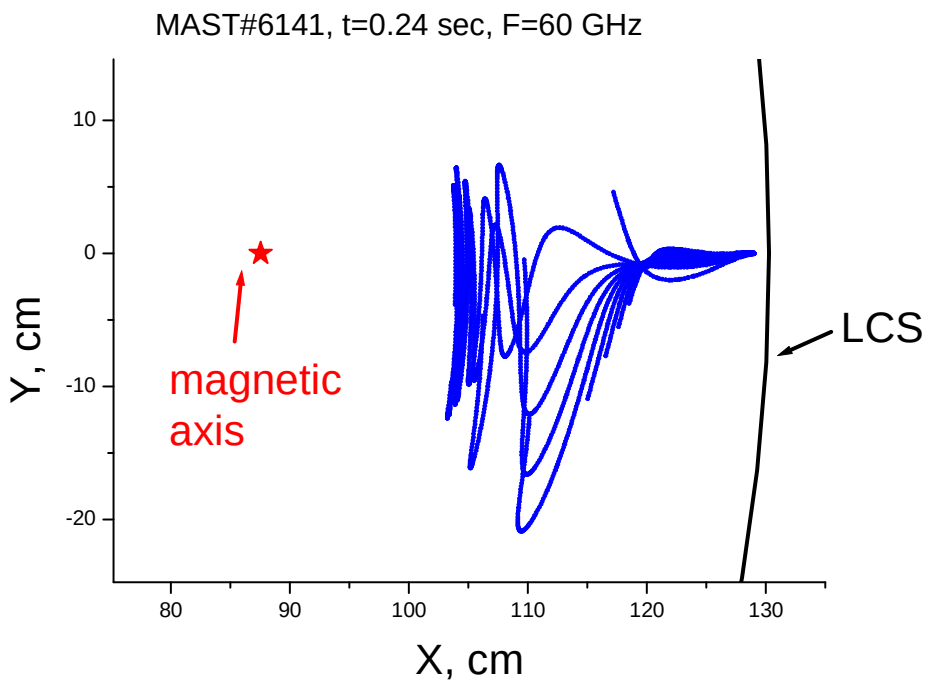
EBW ray-tracing results



Poloidal cross-section of EBW ray-tracing in MAST for 60 GHz launched at optimal angle for target shot parameter



Toroidal cross-section of EBW ray-tracing in MAST for 60 GHz launched at optimal angle for target shot parameter

UKAEA

Fusion Working with Europe

EBWH diagnostics

- Mode conversion process of the high power X-mode to EBW at the UHR layer must be accompanied by the lower hybrid wave generation due to the parametric decay

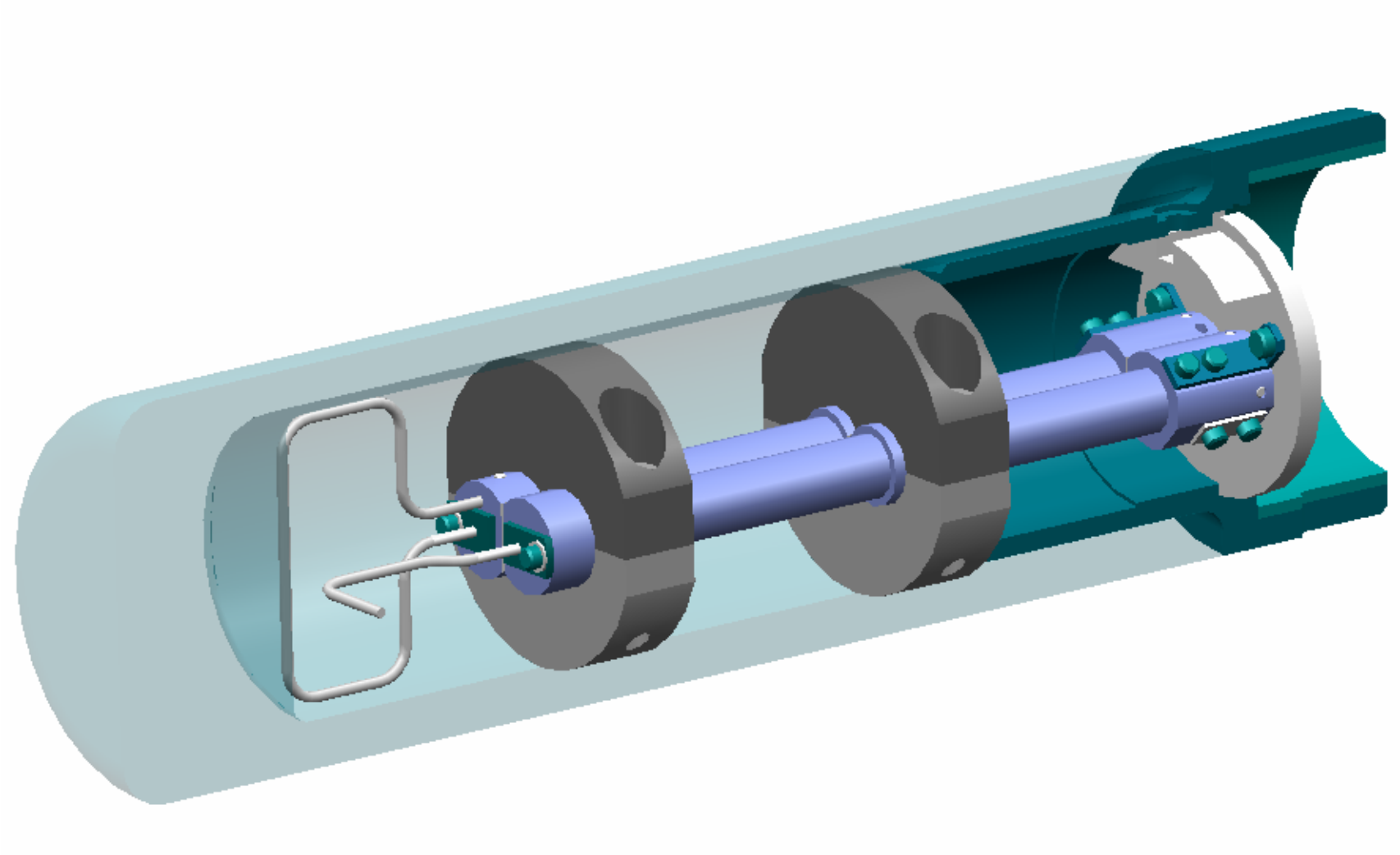
- LH frequencies corresponding to plasma layers where the X-B mode conversion occurs during EBW heating experiments cover the range from 100 MHz to 150 MHz

- LH antenna with the spectrum analyser was developed for the frequency range of 80 - 550 MHz

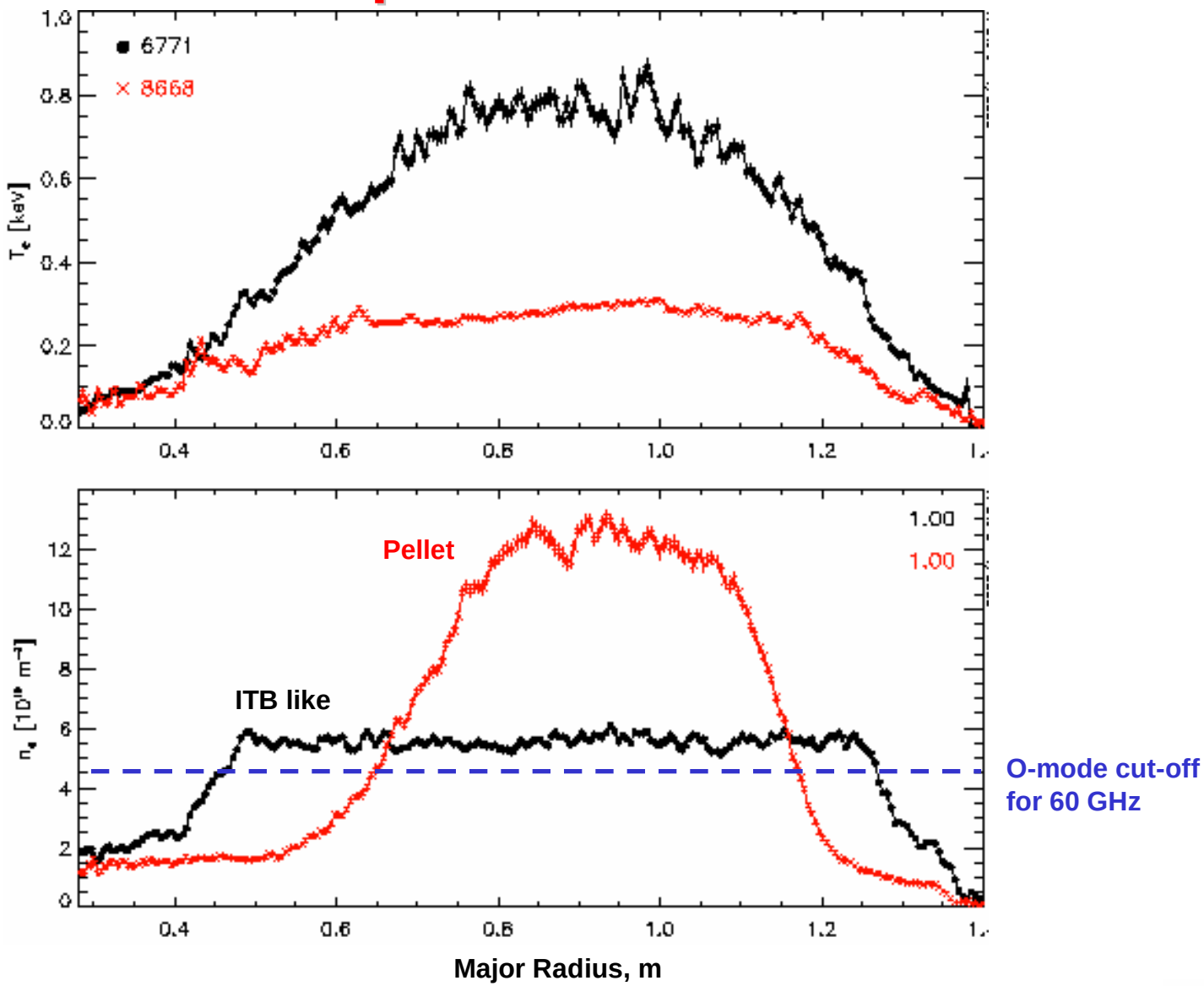
- LH antenna is installed on the reciprocating probe allowing good coupling to LH plasma waves

- Heterodyne radiometer is installed in one of the ECRH transmission lines. It receives plasma emission in exactly reversed way as the gyrotron power entering the plasma.

Lower hybrid antenna for MAST



EBWH plasma scenario



Summary

- EBW steerable launcher has been installed on MAST.

- The new launcher will allow us to conduct EBW heating experiments based on O-X-B mode conversion scheme.

- First ECRH pre-ionisation experiments demonstrated reliable breakdown in pure toroidal field and in the mixture of toroidal and small vertical fields. Preliminary indication of pressure driven currents (~5 kA) has been observed.

- EBW ray-tracing code has been developed in collaboration with Ioffe Institute. It's a powerful tool for the EBW emission interpretation and EBW heating and CD modelling on MAST.

- First EBW heating experiments based on the O-X-B mode conversion scheme have been conducted. Preliminary indication of peripheral RF power deposition has been observed.

Future Plans

Short term:

- **Conduct EBWH experiments with TF scan using EBW plasma scenario. Define TF providing maximum accessibility to the core plasma.**

- **Exploit other scenarios: ITB-like, Pellet and high density L-mode**

- **Conduct fast EBWE measurements during EBWH experiments. Evaluate the applicability of EBWE signals for feedback control.**

Long term:

- **Explore EBW ray-tracing code with different equilibrium codes to find the explanation for the EBWE decay and inverse modulation by ELMs**

- **Low frequency (40 GHz, 2x0.2 MW) EBWH experiments on MAST**

- **Propose a high power (~5 MW) EBWH system for MAST**